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FEASIBILITY STUDY OF THIN PLASTIC MEMBRANE MIRRORS FOR SATELLITE USE

(NASA CONTRACT NASW-100)
FINAL REPORT
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(NASA CR-50,567)

FEASIBILITY STUDY OF THIN PLASTIC MEMBRANE MIRRORS FOR SATELLITE USE

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1. INTRODUCTION AND SUMMARY

a. It was the purpose of this investigation to determine whether mirrors of astronomical precision could be produced for space use using a stretched thin plastic membrane in contact with a ring having a precision circular inner edge that coincides with a plane surface to within approximately 1×10^{-6} inch (1/20 wavelength) or less. A further purpose of the investigation was to determine whether curved mirrors having figure-of-revolution accuracies in the order of 1×10^{-6} inch could be produced using pressure or electrostatic deflection, preferably electrostatic deflection.

b. If such mirrors were found to be feasible on a small scale the development of larger membrane mirrors could then be justified. It was felt that if accurate membrane mirrors in the order of 36 inches in diameter and larger could be developed they would permit substantial reductions in weight and cost relative to ribbed glass, pyrex, or ceramic mirrors. For satellite optical applications the importance of either of these reductions is obvious.

It is also believed that when larger mirrors of astronomical precision are needed for space use the membrane mirror will be the only feasible and economical means of construction.

c. Laboratory-cast collodion membrane mirrors and commercially-available thin plastic film mirrors were investigated using electrostatic and pressure deflection. Laboratory cast membranes were in the order of 10×10^{-6} inch thick and self-adhered in a pre-stressed condition to a precision steel ring. Commercially-available Du Pont Type C Mylar film 250×10^{-6} inch thick was also used in a test fixture having 40 individual radial tension adjustments.

d. The surface texture of laboratory-cast membranes was found to be equivalent to the most perfectly polished optical surface with no texture visible under a phase-contrast system. Flat mirrors of 1×10^{-6} inch accuracy were easily produced. Using electrostatic deflection figure-of-revolution accuracies of 1.5×10^{-6} inch were obtained. This accuracy can be substantially improved. Using Type C Mylar a spherical mirror having a general accuracy in the order of 5×10^{-6} inch was achieved through the use of 40 radial tension adjustments after approximately 3 hours of adjustment by a team of 2 men. However, local surface irregularities in the order of 0 to 5×10^{-6} inch were noted on the Mylar. If these irregularities could be eliminated by greater refinement

of manufacturing techniques by the plastic manufacturer astronomical quality membrane mirrors of substantially greater ruggedness could be produced. It is interesting to note that the 200 inch Mount Palomar mirror also has an irregular surface.

e. Since laboratory cast membranes involve no local surface irregularity problems it is believed that cast membrane mirrors of astronomical quality can be produced up to very large sizes by increasing the scale of present laboratory casting and removal techniques.

f. Since the attainment of a specified figure-of-revolution such as a parabola or sphere was not believed to involve basic problems but only detailed refinements experimental efforts during this investigation were limited to the achievement of high figure-of-revolution accuracy for arbitrary curves which usually were within 10×10^{-6} inch from a perfect sphere. Only by this procedure could the many basic problems have been solved in the short time available for this investigation.

2. LABORATORY APPARATUS

a. In this investigation the apparatus for testing both cast collodion membranes and commercially-available membranes was constructed so that a large number of tests could be made as rapidly and as simply as possible. Therefore, the apparatus shown in Figures 1 and 3 is far heavier than would be designed for satellite use and possesses very slight similarity to the designs envisioned for satellite

use. No attempt was made to design membrane supporting structures of minimum weight since such effort was not considered justified until the basic feasibility of precision membrane mirrors had first been proven.

b. The apparatus shown in Figures 1, 2 and 5 was used to test the collodion type membranes which were cast in our laboratory.

c. Figures 3, 4, 8 and 9 show the apparatus which was used to test commercially-available plastic membranes.

d. The knife-edge test apparatus used for observation and measurement of membrane mirror quality is shown in Figures 6 and 7. A Sylvania Type C-100 crater arc was used to illuminate an 0.008 inch diameter pinhole on one face of a 90° reflection prism. A 2 inch focal length, 16 mm projection lens was used to focus an image of the crater arc upon the pinhole. Two screw-driven cross slides were used for focal and lateral movement of the light source, projection lens, pinhole and vertical knife-edge which were moved as a complete assembly.

e. Collodion membranes were cast on water using the 36 inch diameter x 15 inch deep galvanized steel casting tank shown in Figure 10. The membrane removal card shown inside the tank is shown in greater detail in Figure 11. The removal card was constructed of 3/16 inch brass plate and contained a 9 inch diameter hole the edge of which was tapered to a dull but very smooth knife-edge having an included angle of approximately 30°. The square

guard plates on each side of the removal card were also constructed of 3/16 inch brass and aligned with the card plate by means of dowel pins. The card plate and the two square guard plates were supported in a slotted aluminum bar. The purpose of these guard plates is discussed below under Section 3. The water level used was always sufficient to cover the card plate by approximately ¼ inch.

f. Figures 12 and 13 show the apparatus used for pre-stretching collodion membranes and for bringing the precision support rings into contact with them. Pre-stretching was accomplished by laying the membrane-carrying card upon an aluminum plate having a raised and rounded polished ring one inch smaller in diameter than the removal card hole and membrane. The polished ring was lubricated with mineral oil and pushed the membrane 1/16 inch from its normal free position across the circular knife-edge of the removal card hole. After the membrane was pre-stretched in this manner the precision steel membrane support ring was raised by means of a special lifting fixture having no plunger rotation or side play. Immediately upon being contacted by the highly polished surface of the precision support ring the collodion membrane self-adhered to the ring as shown in Figure 14.

g. Figure 15 shows the evaporation apparatus used to apply the reflective and electrically-conductive metal coatings to all types of membranes. Figure 16 shows a detailed

view of the rotary support for the membrane support ring shown in Figure 15. The 4 inch and 7 inch I.D. precision steel membrane support rings were screwed to the upper or lower discs, respectively. The larger disc, of course, had to be removed when 4 inch rings were rotated. The small motor rotated the membrane support rings at a constant speed of 25 revolutions per minute.

3. CAST COLLODION MEMBRANES

a. The most satisfactory cast collodion membranes were made in the following manner:

(1) The membrane casting solution consisted of the following ingredients and proportions:

16 ml flexible collodion
8 ml non-flexible collodion
24 ml n-amyl acetate
5 drops glyptal
1 drop nitrobenzene

These ingredients were mixed by shaking the container after which the container was placed in the bath of a supersonic cleaner for 30 minutes to insure thorough mixing.

(2) The casting water was ordinary New York City water which was allowed to stand several hours in order to dissipate dissolved gas. Its temperature ranged from 6° to 10°C.

(3) 26 drops of membrane casting solution at laboratory temperature were dropped by means of an eye-dropper upon the center of the casting water surface in the

36 inch diameter tank shown in Figure 10 at the rate of approximately 4 drops/second.

(4) This number of drops resulted in an approximately circular membrane of approximately 24 inches diameter.

(5) Cast membranes were allowed to "dry" or harden on the water surface for a period of 3 to 10 minutes to allow the solvent to evaporate before removal. When the casting water was warmer shorter drying times were used.

(6) Based upon interference measurements (prior to this investigation) of the thickness of similar collodion membranes used in a thermal imaging device the above type cast single membrane will be approximately 5×10^{-6} inch thick, or 10×10^{-6} inch when applied to the removal card as a double membrane.

b. Before casting a membrane the removal card and guard plates were placed on the bottom of the casting tank along a diameter of the tank as shown in Figure 10. Membranes were applied to the removal card by allowing the water in the casting tank to drain slowly so that the water level fell at the rate of approximately 1 inch/minute. This prevented strong turbulence and vortices. As the water level fell the membrane folded over both sides of the removal card and the two square guard plates. This formed a double membrane across the 9 inch diameter hole in the removal card. The guard plates prevented membrane folding irregularities and wrinkles.

c. When this development was begun it was believed that it was necessary to pre-stress the membranes mechanically. Prior to the pre-stressing operation the double membrane was air-dried at 95°C for one hour on the removal card after any remaining water had evaporated. The removal card and membrane were then laid over a polished aluminum ring lubricated with mineral oil as shown in Figure 12. This ring stretched the membrane by pushing the membrane upward 1/16 inch from its free position. The precision membrane support ring was then raised by means of a smooth acting lifting fixture as shown in Figure 13 and brought into contact with the pre-stressed membrane which immediately adhered to it.

d. Knife-edge tests of pre-stressed membranes revealed that adequate figure-of-revolution accuracy could rarely be obtained. This was believed due to inequalities in friction between the membrane and the lubricated aluminum stretching ring which caused corresponding inequalities in membrane tension. Because of these difficulties the air-drying and pre-stressing steps were later abandoned as explained under 7.g. below. This meant that the thick aluminum plate containing the 8 inch diameter polished aluminum ring shown in Figures 12 and 13 was not used.

e. In the procedure finally developed the double membrane on its removal card was placed on the lifting fixture within an average period of 5 minutes after evaporation of any remaining water. The precision steel support ring was then immediately raised and brought into contact with

the membrane which self-adhered to it in less than one second. Precautions were taken to have the laboratory humidity condition uniform and to avoid the breath of laboratory personnel from coming into contact with the membrane before it adhered to the support ring. No membranes were applied in humidities below 30%.

4. METAL-COATING OF CAST COLLODION MEMBRANES

a. Previous work in connection with infrared detectors required both metallic gold and gold-black to be deposited by evaporation upon thin collodion membranes. Since the laboratory set-ups were readily available at the time this investigation began gold was used to provide the electrical conductivity and optical reflectivity necessary to test collodion membrane mirrors using electrostatic deflection. However, many other metals could have been used in lieu of gold or could have been deposited over the gold coatings to obtain better reflectivity in the blue and ultra-violet regions.

b. At the beginning of this investigation collodion membrane mirrors were originally coated with the hot gold source and mirror in fixed positions. This method of evaporation resulted in very poor figure-of-revolution accuracy under electrostatic deflection. Since it was previously known that when most metals are evaporated upon a thin collodion membrane the stiffness of the membrane is increased it was assumed that the poor figure-of-revolution accuracy was due to irregularities in the thickness of evaporated gold. Accordingly, the precision steel membrane support

rings were screwed to the motor-driven disc shown in Figure 16 which rotated at 25 RPM during evaporation. The membrane side of the ring faced downward. The stationary gold-heating filament was located approximately 2 inches from the rotational axis approximately 4 inches below the membrane surface. This method of evaporation resulted in back-coated rather than first surface membrane mirrors. This method of coating was selected merely because it permitted the support rings to be more easily mounted on the rotary evaporation support. The heater was adjusted to evaporate gold at 1 micron pressure at a slow rate over a period of 10 minutes or 250 revolutions. As a further step to insure maximum figure-of-revolution uniformity the gold heater filament temperature was slowly raised to its working temperature over a period of about one minute and slowly lowered at the same rate. Usually two such coatings were applied to obtain a gold coating that appeared dark green by transmitted light.

c. Due to rotation of the membrane during evaporation this procedure produced extremely uniform circumferential distribution of the gold coating on the membrane. However, the radial distribution of the gold was found to be less concentrated at the periphery than at the center. When electrostatic deflection was applied the resulting optical figure of the coated membrane was a highly accurate figure-of-revolution of the form generally referred to as an oblate sphere. The longer radius of

curvature at the center of this figure was due to the greater thickness of gold deposition at the center which caused the membrane stiffness to be greater at the center.

d. Such deviations of the figure-of-revolution from a sphere or parabola can be corrected at a later stage of this development when the necessary time is available to determine the location of the gold or other metal source which will produce the proper radial distribution of the metal coating. It is important to note that control of the radial distribution of the evaporated metal coating offers an accurate "fine-adjustment" means for obtaining any desired aspheric or spherical figure of membrane mirrors. This control may be accomplished by varying the position of the gold source from the rotational axis or by interposing a properly-curved aperture between the gold source and the membrane.

5. EFFORTS TO PRODUCE THICKER CAST COLLODION MEMBRANES

a. The type of collodion membranes described above under Section 3. were selected for use after a brief intensive attempt to produce substantially thicker membranes. This brief effort revealed that the development of substantially thicker than 10×10^{-6} inch cast membranes might require more time than was available for the complete investigation of feasibility of membrane mirrors. When this possibility became apparent it was decided to investigate and demonstrate the feasibility of precision membrane mirrors using the thinner membranes which had already been developed and found to be highly satisfactory

except for their thinness.

b. Efforts to produce thicker cast membranes proceeded in two directions as follows:

(1) Multiple ply membranes were produced by allowing one or more membranes of the type described under Section 3. to fold over the first double membrane on the removal card. The original double membrane and each additional double membrane deposited over it was baked for approximately 30 minutes at 95°C before the next double membrane was deposited. To compensate any small variations in the thickness of each membrane the second membrane was deposited with the removal card rotated 180° from its original position in the casting tank. The third membrane was deposited with the removal card 90° from its original position. The fourth membrane (actually the seventh and eighth single membranes) was also deposited with the removal card 90° from its original position but in the 180° opposite direction. In this manner a relatively large number of membranes could be used. As many as four successive overlays (eight single membranes) were successfully produced but the total number feasible appears to be limited only by the degree of effort expended to avoid accidental flaws which require the multiple ply membrane to be discarded. No difficulty was encountered in applying four ply double membranes to the precision steel support rings provided that

application occurred within 5 minutes or less after removal from the water tank. Better adherence could be obtained when this time was reduced.

(2) Single ply membranes of substantially greater thickness were first attempted by merely utilizing a much larger amount of the film casting solution specified in Section 3. This resulted in thicker membranes but also large uniformity variations which were easily visible when observed by means of the schlieren test system. The resulting membranes also showed wide interference color variations while on the casting water surface after hardening. In an effort to improve the uniformity of thicker membranes the following "spot check" experiments were made to determine the influence of the following factors and to obtain a better knowledge of the phenomena involved in membrane casting:

(a) Laboratory air drafts. Experiments ranging from the use of a plate two inches above the casting water surface to eliminate room air drafts to the use of a fan blowing air over the tank at the rate of one to two feet/second resulted in no significant improvement or change in the degree of uniformity.

(b) Casting water circulation. Great care was exercised to minimize residual water currents by inserting metal baffles but no significant improvement resulted since the water was

usually allowed to become "quiet" for 15 - 30 minutes before casting a membrane.

(c) Casting water ripples and waves. Previous tests had shown that thinner optimum membranes could be cast consistently without difficulty provided that short wavelength ripples due to building vibrations were eliminated by mounting the casting tank on three foam rubber pads. The very low amplitude, long wavelength waves which were present 15 minutes after filling the tank were found to cause no difficulty when thinner membranes were cast. However, no improvement in the uniformity of thicker or thinner membranes was noted when the foam rubber shock mounts were made softer in order to reduce ripples and waves to a substantially greater degree.

(d) Amount of solvent in film casting solution. On the assumption that non-uniformities might be caused by local drying before the film solution had spread evenly over the water surface several times the proportion of n-amyl acetate specified in Section 3. was added in an effort to lengthen the time required for the membrane to harden. These experiments yielded no significant or consistent improvements in membrane uniformity.

(e) Variations in membrane casting solution ingredients. The proportions given in Section 3.

were varied and various solvents such as amyl acetate, benzyl acetate, alcohol, acetone, lacquer thinner, glyptal, and nitrobenzene were added to or substituted for the n-amyl acetate normally used. No significant improvement in uniformity was achieved.

(f) Casting water additives. Various materials such as aerosol, salt, sugar, gelatin, gum arabic, "glim", alcohol, glycerine and n-amyl acetate were added to the casting water with no significant improvement in uniformity. A small amount of gelatin appeared slightly beneficial, perhaps due to the damping of water currents caused by the increased viscosity of the gelatin-water mixture.

(g) Water temperature. Variation of the casting water temperature revealed that the most uniform membranes of all thicknesses were obtained for low water temperatures in the range 6° to 10°C, as supplied by New York City during the winter season. Warmer water presumably caused too high a rate of solvent evaporation. Due to the problem of cooling the tank water temperatures below 6°C were not tried. However, there appears to be no indication that membrane uniformity will be materially improved at lower water temperatures.

(h) Rate of applying film-casting solution to the water surface. Experience in the casting of membranes as outlined in Section 3. has shown that best results are obtained when the film casting solution is dropped on the casting water at the rate of approximately 4 drops/second with the dropper not more than 3/16 inch above the water. No improvement in the uniformity of thicker membranes could be achieved by varying this rate or by placing the dropper nearly in contact with the water surface in order to prevent the small ripples produced by the solvent drops.

(i) Dropping of the membrane casting solution from a multiplicity of nozzles. An experiment was run using seven eye-droppers to drop the casting solution on the water surface simultaneously. The droppers were located at the corners and center of a hexagon having 9 inch sides. While no improvement resulted in the uniformity of thicker membranes cast in the above manner the multiple dropping technique appears extremely promising as a means for casting membranes of the type described in Section 3. over very large areas when larger membranes are required. This method of casting and the thickness relationships shown in Figure 18 should be investigated more

thoroughly when work is again resumed on membrane mirrors.

(j) Quantity of casting solution vs. membrane diameter and thickness. Using the 36 inch diameter casting tank and auxiliary 21 and 10.25 inch diameter containers the relationship between the number of drops used to cast various collodion membranes and their diameters was obtained. This relationship is shown in Figure 17. From the above data the corresponding thicknesses of the liquid film casting solution immediately after being dropped upon the water surface were computed on the assumption that the liquid solution assumes very nearly uniform thickness before drying. Based upon the known fraction of volatile components in the casting solution the ratio of the dry volume of a cast collodion membrane to the original volume of the film-casting solution used was computed. Figure 18 was then prepared using this volume ratio and the wet thicknesses computed above. Using the 36 inch tank it will be seen from Figure 18 that the standard 26 drop membrane has a thickness of 4.9×10^{-6} inch. When folded over the removal card the resulting double membrane will have a thickness of approximately 9.8×10^{-6} inch. This is in excellent

agreement with the 10×10^{-6} inch round figure used for convenience throughout this report.

6. LAPPING OF MEMBRANE SUPPORT RINGS

a. Three 7 inch and two 4 inch diameter precision steel membrane support rings were turned from Ketos steel tube stock and hardened. The inside surface of the ring close to the precision flat surface was first highly polished using optical rouge on a wood stick. The precision flat surface of each ring was then ground flat successively against fine-ground glass laps using 4F Carborundum, 5 micron and 0 to 0.5 micron diamond dust respectively. Kerosene was used as a non-rusting vehicle for each of the above abrasives. By this means the inner edge was lapped "molecularly" sharp and turned-down edge was eliminated.

b. Three 26 inch diameter x 1 inch plate glass laps were prepared for the above precision ring grinding process by successively grinding each glass disc with another until all were flat. When flatness was achieved the surfaces were fine-ground using 4F Carborundum. Each glass tool was used with only one of the three grades of abrasives listed above.

c. Support rings were tested using an 8 inch diameter Pyrex test flat accurate to 1/20 wavelength. No great difficulty was experienced in lapping a 7 inch diameter support ring flat to within 1/20 wavelength within eight hours so that only a single interference color appeared around its inside edge when viewed through the test flat.

d. Only one out of 5 steel rings ground as described above did not remain flat. This spurious ring was cycled from cold to boiling water several times and relapped to 1/20 wavelength. It has shown no further departures from flat since being reworked.

7. TEST RESULTS USING COLLODION MEMBRANE MIRRORS

a. The first experiments conducted with the apparatus shown in Figure 1 utilized 7 inch diameter membranes produced as described under Section 3. The optical figures originally obtained using electrostatic deflection were far from accurate figures-of-revolution. This led to the procedure of rotating the mirror relative to the gold source during evaporation as described under Section 4.

b. While rotary evaporation eliminated nearly all random irregularities gross astigmatic errors still remained. It was suspected that these were due to gradual variations in the thickness or stiffness of the membrane across the removal card hole diameter. To investigate this condition two-ply and four-ply membranes were produced as described under Section 5. above in an effort to compensate such effects since, when a second membrane is cast over an original membrane, a thick region should, to a first order approximation, be compensated by a thin region. This would be true of the third and fourth membranes cast over the first and second. Unfortunately, such two and four ply membranes showed only slight improvement. In addition, a removal card was tried

having a square hole with sides equal to the diameter of the circular hole in the removal card shown in Figure 11. No uniformity improvement was noted using single ply membranes removed with this card. Based upon tests of three membranes made using the square hole it appears that the shape of the hole in the removal card is far from critical.

c. The flatness of the mirror membrane support rings were suspected and checked. It was found that one of the support rings had deviated about one wavelength from flat. This condition was easily corrected by regrinding the ring on the 0 to 0.5 micron glass lap. The other rings were found to be still flat to about 1/20 wavelength. Subsequently, all precision rings were checked for flatness prior to applying each new membrane for test. It was not found necessary to re-lap a ring for any other reason than to restore a sharp inner edge. The "molecularly" sharp edges were often dulled by the most gentle use of lens or "Kleenex" tissue. No significant improvement in figure-of-revolution uniformity resulted from these changes.

d. The flatness of the aluminum electrode plate was suspected and checked by turning it to its four 90° mounting positions relative to the membrane when electrostatically deflected. Corresponding rotation of the distortion pattern as viewed via the schlieren system proved that it had warped. It was then reground flat to within approximately 0.0001 inch against a flat glass

plate using 4F Carborundum. When again tested by rotation the electrode caused no observable change in the knife-edge shadows. Subsequently, similar checks were made by rotating the electrode when each new membrane was tested but it was not found necessary to regrind it. While correction of the electrode errors resulted in some improvement of figure-of-revolution uniformity variations in the order of one to two wavelengths still persisted.

e. On one occasion the rubber gasket shown on Figure 1 between support ring 9 and support plate 7 was too tightly compressed and caused distortion of the support ring and membrane which could be eliminated when the gasket compression was reduced. To eliminate any possibility of recurrence of this distortion the solid rubber gasket was replaced by four softer foam rubber washers at each of the four mounting screw positions.

f. It was next assumed that the uniformity difficulties might be due to the fact that the diameter of the piece of collodion membrane used was only 9 inches while the diameter of the membrane mirror was 7 inches, or nearly as large. It was thought that the 9 inch diameter membrane might be sufficiently uniform over only a central area, perhaps half its full diameter. Therefore, two 4 inch diameter Ketos steel membrane support rings were quickly made and tests resumed with the apparatus modified as shown in Figure 1. These tests showed some slight improvement but figure-of-revolution accuracy was still

far from acceptable.

g. It is important to note that when the above experiments were made the stretching procedure described above under 3.c. was employed. However, after the first tests of the 4 inch diameter rings yielded only slight improvement it was decided to delete the stretching procedure and to use greater care in transferring the membrane to the 4 inch diameter support ring. Precautions were also taken to prevent humidity variations over the membrane by exercising care to avoid the breath of the person performing the work from blowing close to the membrane. A silica gel dryer package was also fastened inside the metal spacer plate 8 shown in Figure 1. When these changes were made a very great improvement in uniformity was achieved using an optimum single ply membrane of the type described under 3.a., 3.b., and 3.e. above. Its optical figure is discussed in detail below.

h. Figure 19 shows a typical shadow pattern as obtained for a gold-coated 4 inch diameter single ply membrane mirror with the above improvements. A deflection voltage of 4900 volts and an electrode spacing of 0.4 inch produced an average test radius of 86 inches. The focal lead screw and a calibrated vernier control in the high voltage supply circuit were both used to determine the difference between the radius of curvature at the outer edge and at the center of the membrane. The mechanical and electrical methods of overall radius variation measurement

checked each other within less than 5%. These measurements revealed that the radius of curvature was 0.21 inch longer at the center than at the edge. This meant that the general mirror figure was an oblate spheroid. When both the pinhole and knife-edge move together the radius of curvature variation C for a parabolic mirror is $r^2/2R$ where r is the mirror radius and R is its average radius of curvature. Using this relation we obtain the figure 0.023 inch for C. Therefore, the membrane mirror had a variation of radius of curvature approximately .21/.023 or 9.1 times greater than for a parabolic mirror of the same average radius of curvature and diameter. The maximum deviation D of a parabola from the nearest average circle is very close to $\frac{r^4}{24R^3}$. Using this relation for a 4 inch diameter mirror of 86 inch average radius we find that D equals 1.05×10^{-6} inch. Since the membrane mirror figure had 9.1 times the curvature variation of a parabola its maximum deviation from an average sphere was approximately $9.1 \times 1.05 \times 10^{-6}$ or 9.5×10^{-6} inch. Using the calibrated voltage controls it was observed that the maximum irregularity of the knife-edge pattern (as shown in Figure 19) could be compensated by a 0.03 inch change in the radial adjustment of the pinhole and knife-edge assembly. Therefore, the maximum irregularity (deviation from a perfect figure-of-revolution) was $\frac{.03}{.21} \times 9.5 \times 10^{-6}$ or 1.36×10^{-6}. The round number 1.5×10^{-6} inch

is therefore given as the order of accuracy of the 4 inch diameter collodion mirror.

i. Since the contract funds were nearly expended at this point no time was available to run more than one other test similar to the above or to re-check larger 7 inch diameter or double-ply membranes using the revised procedures outlined under 7.g. above. In the short time which remained it was considered important to investigate commercially-available membranes as described below under Section 8.

j. It is important to note that when collodion mirrors were not deflected they were exceedingly good flats having a "perfect" polish, no small surface irregularities, and general accuracy as high as that of their metal support rings which was 1/20 wavelength (1×10^{-6} inch) or better.

k. Due to their thinness all collodion membranes vibrated noticeably in response to shock impulses. However, the amplitude and duration of such vibrations was much less for 4-ply than for single-ply membranes.

l. The high voltage supply shown in Figure 2 worked exceedingly well and permitted the very fine vernier adjustments of membrane radius needed for schlieren observations to be made with ease. No difficulty was experienced due to voltage drift.

8. <u>TEST RESULTS USING COMMERCIALLY-AVAILABLE PLASTIC MEMBRANES</u>

a. The apparatus shown in Figure 3 was first set up using Du Pont Teslar 0.0005 inch thick with no metal coating applied. Deflections of the membrane were produced by

means of the apparatus shown in Figure 4. It was found that the membrane tension could be adjusted very easily by means of the 40 set screws. The first accurate average spherical figure was achieved after approximately 8 hours during which the knife-edge shadows were viewed by one man while a second man adjusted the set screws as specified by the first man.

b. Figure 20 shows a typical schlieren knife-edge test pattern for an uncoated Du Pont Teslar membrane 0.0005 inch thick when deflected to an 86 inch radius of curvature. Since the membrane had no metal coating the shadow patterns represent the combined irregularities of both surfaces. These combined irregularities were estimated to be in the order of 10×10^{-6} inch and are clearly visible in Figure 20. This material also has an undesirable turbid characteristic which reduces the shadow contrasts.

c. Figures 21, 22, and 23 show a schlieren knife-edge test pattern and single and multiple line Ronchi grid test patterns, respectively, for a Du Pont Type C Mylar membrane 0.00025 inch thick and gold-coated upon its first surface when deflected to an 86 inch radius of curvature. It may be noted that Type C Mylar shows excellent shadow contrasts when viewed by schlieren knife-edge and produces negligible scatter due to turbidity. It was estimated that the local irregularities shown represent surface variations in the range from 0 to 5×10^{-6} inch. The poorer contrast of the Ronchi patterns is due to

diffraction effects caused by the grid.

d. After experience totaling approximately three days a team of two men could adjust a Type C Mylar membrane to within 5×10^{-6} inch or less from spherical (except for the small uncompensatable local irregularities) within about three hours. It was found that the initial coarse adjustments could be made most rapidly using Ronchi viewing adjusted to show two to four lines. Future adjustments of this type might be further simplified by using a pair of 90° crossed grids instead of a single grid so that the errors in mirror figure may be observed simultaneously along two axes. Fine adjustments were more easily made using simple schlieren knife-edge viewing of the mirror figure.

e. The suction apparatus shown in Figure 4 worked exceedingly well and permitted the very fine vernier adjustments of membrane radius needed for schlieren or Ronchi observations to be made with ease.

f. While the above surface irregularities are large it is interesting to compare them with the knife-edge test patterns obtained with the 200 inch mirror of the Hale telescope at Mount Palomar Observatory. (1) The 200 inch mirror knife-edge patterns appear to show small

(1) Final adjustments and tests of the Hale telescope, Publications of the Astronomical Society of the Pacific, 1950, Vol. 62, Pages 91 - 97.

local surface irregularities comparable to those which appear in Figure 21. This suggests an interesting question: How closely would a 200 inch Type C Mylar membrane mirror compare with the actual 200 inch ribbed pyrex mirror?

g. Due to its great thickness and surface tension the 4 inch diameter Mylar membrane mirror showed negligible vibrational response to gentle tapping of the support structure with a metal tool. Apparently, shock-excited vibrations are damped out within a fraction of a second.

9. CONCLUSIONS

a. Cast Collodion Membrane Mirrors

(1) Cast collodion double membranes in the order of 10×10^{-6} inch thickness can be produced having negligible local surface irregularities and a "polish" equivalent to the most perfectly polished glass optical surface. This "polish" is not degenerated by evaporation of gold upon its surface. These membranes possess sufficient thickness and stiffness uniformity to permit figure-of-revolution accuracies of at least 1.5×10^{-6} inch to be obtained when a single ply membrane is adhered to a 4 inch diameter precision steel ring which is flat to 1×10^{-6} inch. This accuracy may be obtained after evaporation with gold and using electrostatic deflection.

(2) Since little time was available for further refinements and tests after high accuracy was finally

achieved it is probable that the 1.5×10^{-6} inch accuracy figure obtained can be improved significantly and that much larger mirrors can be produced having good accuracy.

(3) The stiffness of a cast collodion membrane is increased by deposition of gold and many other metals upon it. It is therefore necessary to rotate a cast collodion membrane about its intended optical axis during evaporation of the metal in order to obtain an accurate figure-of-revolution. By controlling the radial distribution of the metal during evaporation it should be possible to obtain fine control of the figure of a membrane mirror.

(4) Control of the position and size of a flat electrode and its potential difference relative to the membrane will provide control of the figure of a membrane mirror over a wider range. The electrode may also be curved in order to achieve control of the mirror figure. The edge-to-edge surface accuracy of the electrode can be at least 10 times poorer than that desired of the membrane mirror and the electrode does not need to be polished. Only a relatively coarse ground surface is necessary. Electrode accuracy becomes less critical as its size decreases and as its spacing increases relative to the membrane.

(5) Both 4 inch and 7 inch diameter precision steel membrane support rings can be lapped flat to within

1×10^{-6} inch in approximately one day.

(6) Multiple-ply double collodion membranes can be successfully produced up to at least 4-ply double membranes.

(7) One to four ply double collodion membranes adhere without difficulty upon contact with a clean, polished steel membrane support ring within less than one second. Experience obtained prior to this investigation has proven that collodion membranes adhere even more firmly to polished glass or ceramic surfaces.

(8) Membranes must be adhered to their precision support rings in a draft-free atmosphere of uniform humidity, preferably over 30%.

(9) Based upon experience using from one to four ply double membranes it should be possible to produce at least 10 to 20 ply double collodion membranes (100 to 200 $\times 10^{-6}$ inch thick). If difficulty is experienced in obtaining contact adherence of such thick membranes they can be utilized in the same manner as commercially-available membranes such as Du Pont Mylar.

(10) Due to their extreme thinness single-ply double collodion membranes are very sensitive to vibration. However, if their thickness is increased, as in the case of 4-ply double membranes, the effect of vibration is reduced very significantly. When 10 and 20 ply double membranes become available the effect of vibration will probably be negligible, as in the case of the commercial membranes.

(11) To prevent distortion of the optical figure great care must be exercised to prevent vertical, lateral, or rotational displacement of a collodion membrane relative to its precision support ring at the time adherence occurs. Membranes must be transferred directly to their support rings without previous mechanical stretching. When used in vacuum or in air at any constant humidity the optical figure of a collodion membrane mirror will not vary.

(12) The optical damage caused by accidental small perforations of the membrane covers an area approximately five times the diameter of the actual perforations. This offers a clue as to the order of damage which will be produced by meteorites.

b. Commercially-Available Plastic Membrane Mirrors

(1) A very satisfactory means for adjusting the radial tension of commercially-available membranes at 40 points around the mirror circumference has been developed. With it gold-coated membrane mirrors can be adjusted by two men to an average spherical figure within approximately 5×10^{-6} inch within a few hours. If more time is devoted to adjustment it should be possible to achieve 1×10^{-6} inch uniformity or better. However, due to surface irregularities of the plastic materials tested closer adjustments were not attempted. Once adjusted to a desired figure this type of membrane mirror appears to retain its optical figure

indefinitely.

(2) Only 0.0005 inch thick Du Pont Teslar and 0.00025 inch Du Pont Type C Mylar were tested. Teslar produces a prohibitive amount of light scatter due to a turbid surface condition and therefore is not satisfactory for optical purposes. Type C Mylar possesses a "highly-polished" optical surface which produces negligible light scatter. However, it does possess small local surface irregularities estimated to range from 0 to 5×10^{-6} inch. For precision optical purposes these surface irregularities must be reduced by approximately one order of magnitude.

(3) The vibrational response of a 4 inch diameter Mylar membrane mirror to shock excitation is negligible and is damped out within less than one second.

c. The results of this brief investigation are considered highly promising. At the present stage of investigation the membrane method appears to offer a potentially far less expensive and lower weight method of construction of large mirrors (36 inches and larger) than the use of solid glass or ceramic materials. The membrane method appears to offer the only practical means for constructing very large mirrors for space use (70 inches and larger).

10. RECOMMENDATIONS

a. As indicated above it has been concluded that cast collodion membrane mirrors can be made to accuracies

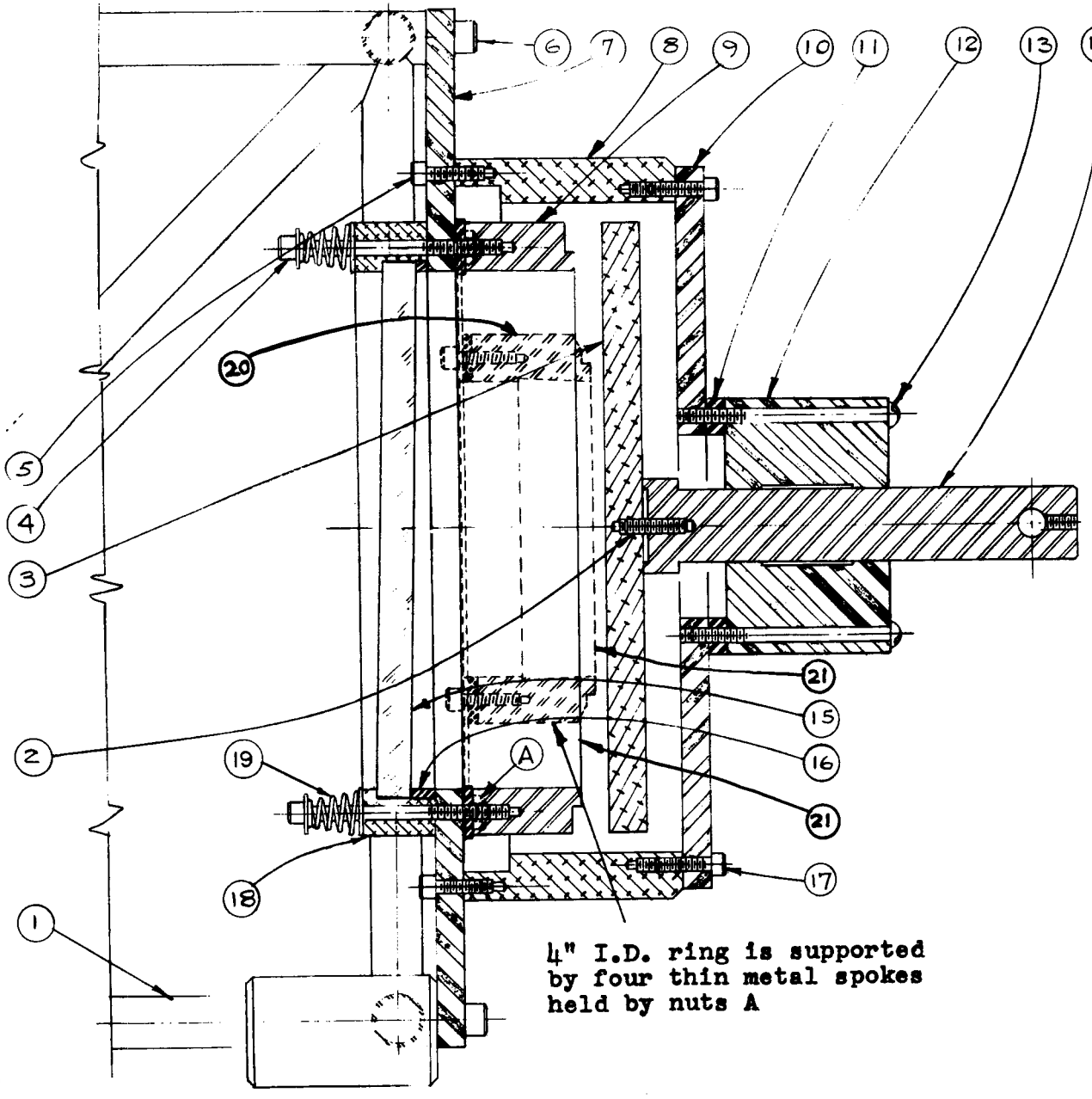
sufficiently high for astronomical use in space. However, since favorable experimental results with small test mirrors were obtained only a very short period prior to the time that the contract funds became exhausted their ultimate limitations were not determined. It is therefore recommended that:

(1) Apparatus and techniques for utilizing laboratory-cast and commercially-available membranes should be further refined so that their accuracy, thickness, and environmental limitations can be more precisely determined. All potentially useful commercially-available plastic films should be investigated. These experiments could be conducted using the present 4 inch and 7 inch mirror test apparatus now available.

(2) Since thicker, commercially-available membranes now appear feasible for precision optical use provided their surface accuracy can be improved by about one order of magnitude it is recommended that a prototype membrane objective mirror in the 24 to 36 inch diameter size range capable of utilizing Du Pont Type C Mylar and similar materials now be attempted. Such a larger mirror, when successfully developed, would provide a firm justification for the development of much thicker, multiple-ply cast collodion membranes or for the cost of development of thin plastic films of greater surface smoothness by one or more of the large plastic manufacturers.

(3) Small diameter collodion membrane mirrors cast in our laboratory have already proven capable of providing optical surfaces of astronomical quality and offer the most certain means for constructing large astronomical mirrors within the shortest period of time. Therefore, it is recommended that a prototype membrane mirror of the laboratory cast type having a diameter in the range from 24 to 36 inches and an accurate parabolic figure be attempted. Such a larger mirror, when successfully developed, would permit the design and construction of evaluation models for space use to be undertaken.

APPARATUS FOR TESTING CAST COLLODION MEMBRANES WITH MEANS FOR ELECTROSTATIC DEFLECTION



Principal Parts

3 - Electrode disc

7 - Texolite support plate

8 - Metal spacer plate

9 - 7" I.D. Steel support ring

10 - Texolite support plate

11 - Rubber compression washer

12 - Nylon insulating bushing

13 - Electrode parallelism adjustment screws

14 - Metal electrode support

15 - Glass anti-draft window

20 - 4" I.D. Steel support ring (when used)

21 - Collodion membrane

FIGURE 1

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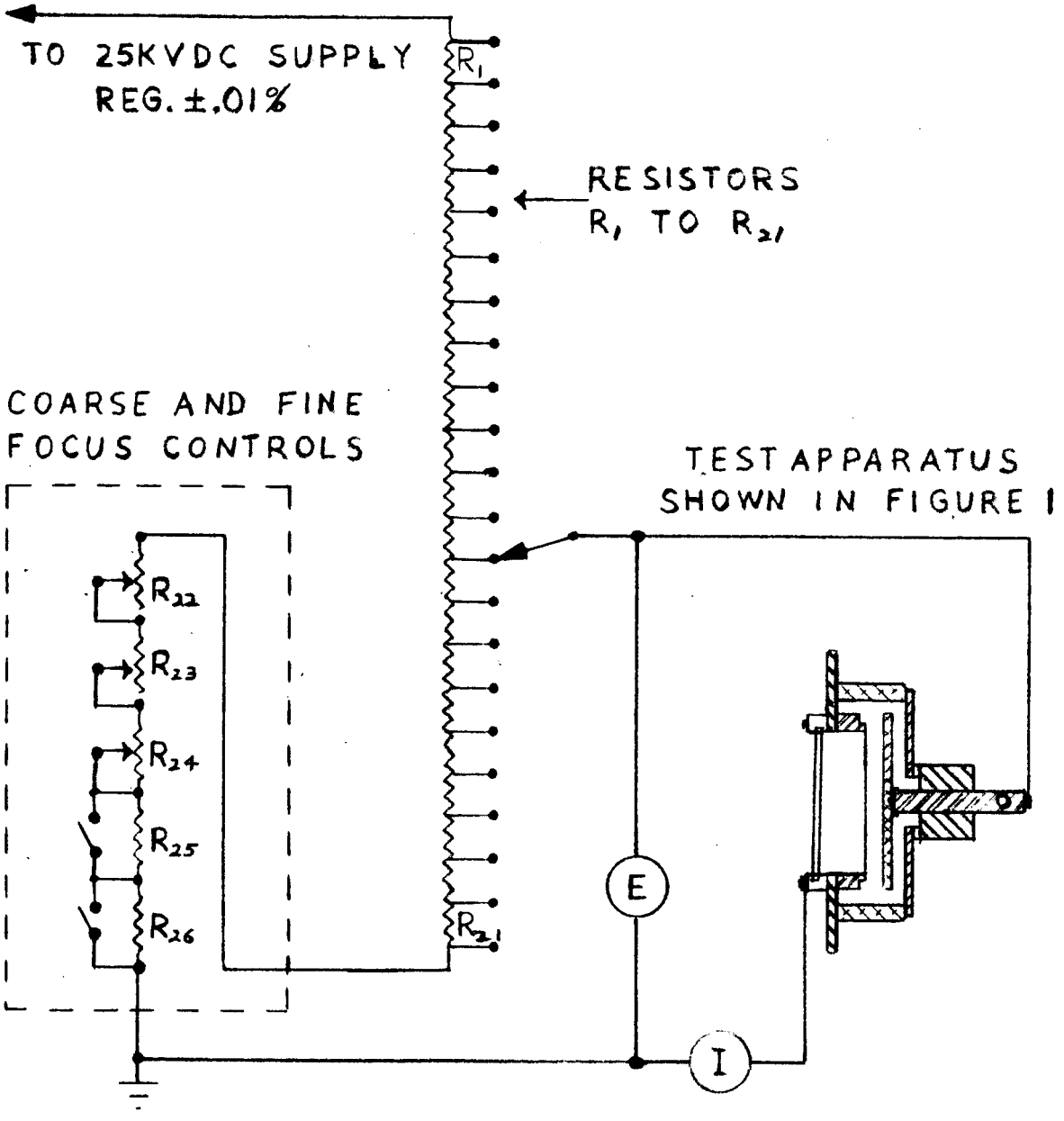
HIGH VOLTAGE SUPPLY FOR DEFLECTING CAST COLLODION MEMBRANES



R_1 TO R_{21}	22	MEG. OHM EACH.
R_{22} AND R_{23}	3	" " "
R_{24}	7.5	" "
R_{25}	3	" "
R_{26}	22	" "

FIGURE 2

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APPARATUS FOR TESTING
COMMERCIALLY AVAILABLE MEMBRANES WITH
MEANS FOR ADJUSTMENT OF RADIAL TENSION

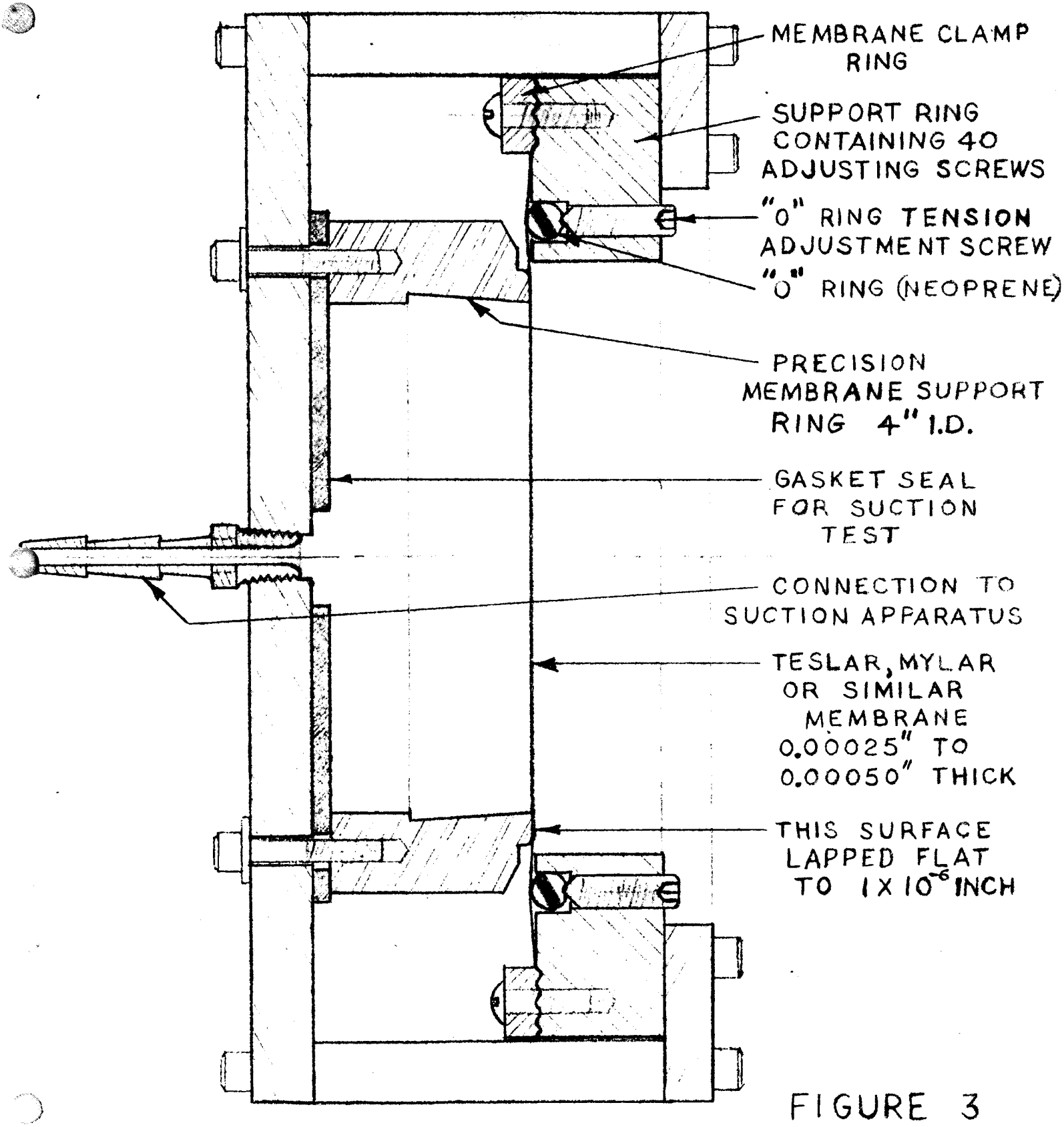
MEMBRANE CLAMP RING
SUPPORT RING CONTAINING 40 ADJUSTING SCREWS
"O" RING TENSION ADJUSTMENT SCREW
"O" RING (NEOPRENE)
PRECISION MEMBRANE SUPPORT RING 4" I.D.
GASKET SEAL FOR SUCTION TEST
CONNECTION TO SUCTION APPARATUS
TESLAR, MYLAR OR SIMILAR MEMBRANE 0.00025" TO 0.00050" THICK
THIS SURFACE LAPPED FLAT TO 1 X 10⁻⁶ INCH

FIGURE 3

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VACUUM GENERATING APPARATUS FOR DEFLECTING COMMERCIALLY AVAILABLE MEMBRANES

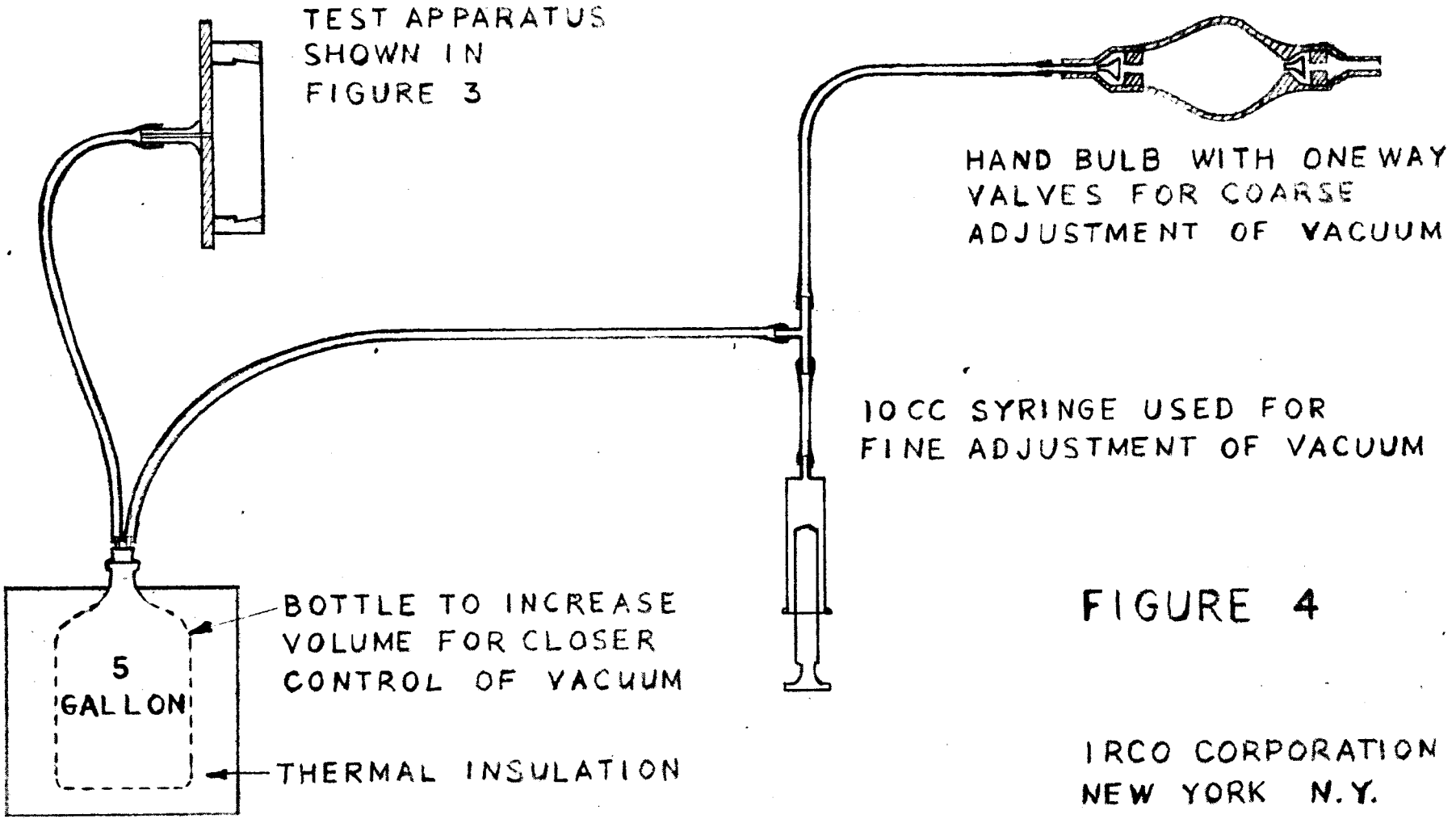
TEST APPARATUS SHOWN IN FIGURE 3
HAND BULB WITH ONE WAY VALVES FOR COARSE ADJUSTMENT OF VACUUM
10 CC SYRINGE USED FOR FINE ADJUSTMENT OF VACUUM
5 GALLON
BOTTLE TO INCREASE VOLUME FOR CLOSER CONTROL OF VACUUM
THERMAL INSULATION

FIGURE 4

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IRCO CORPORATION

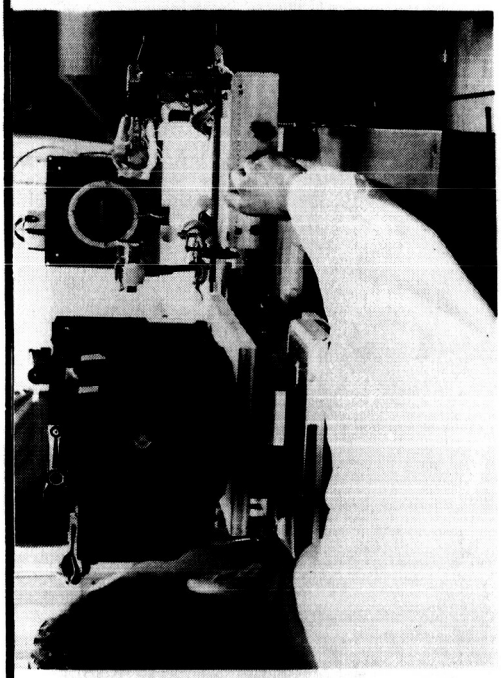

FIGURE 6

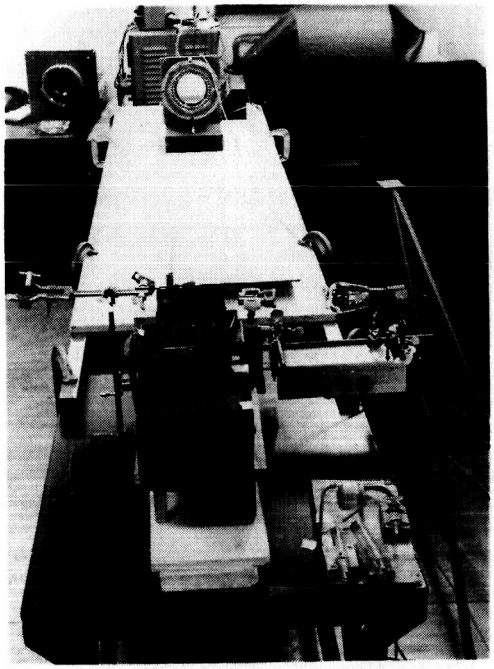

FIGURE 8

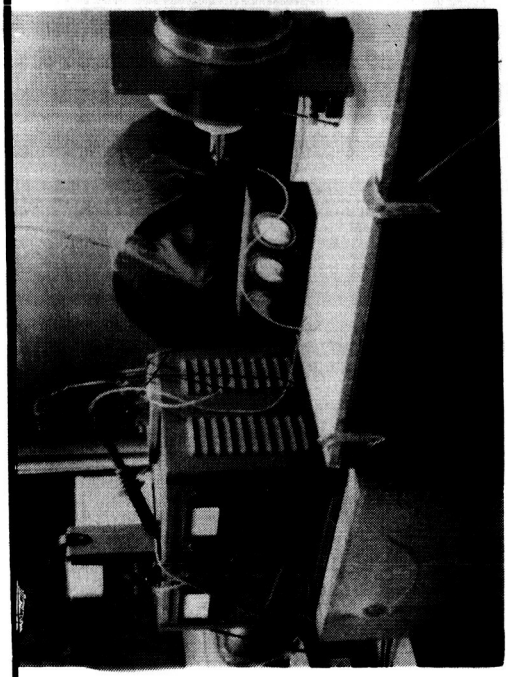

FIGURE 5

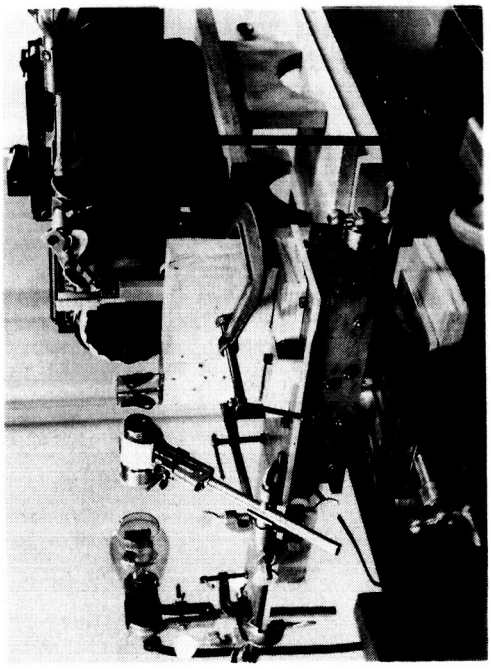

FIGURE 7

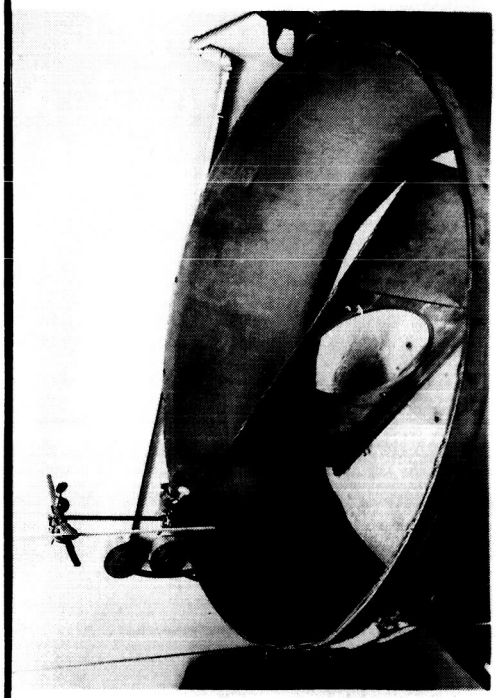

FIGURE 10

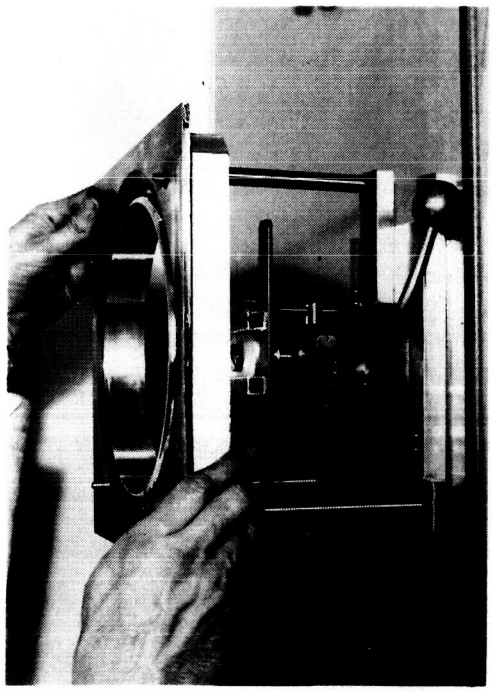

FIGURE 12

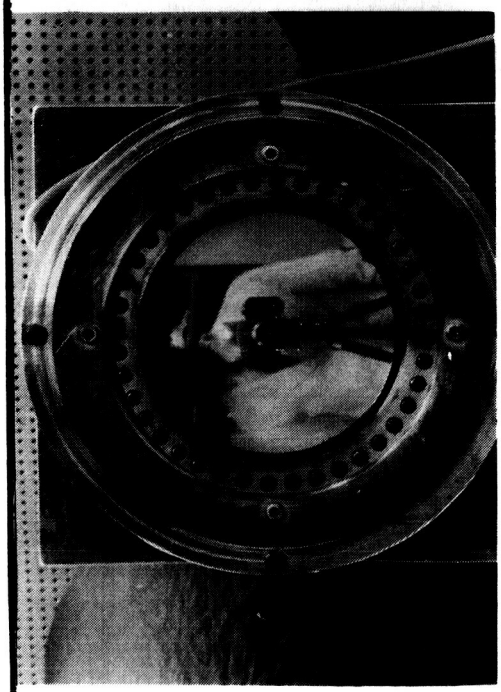

FIGURE 9

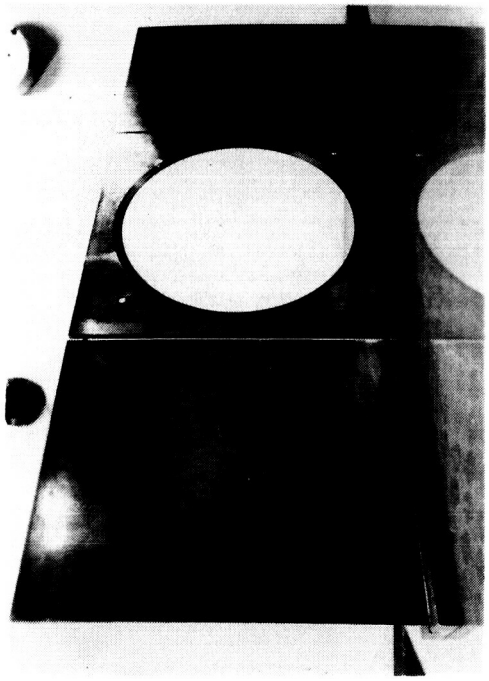

FIGURE 11

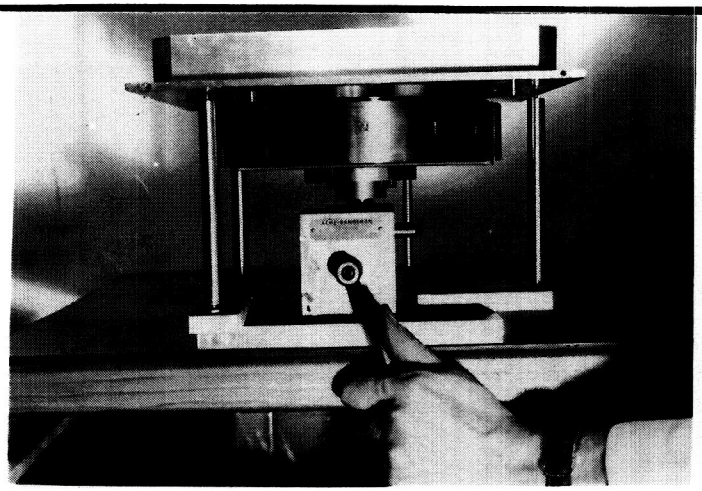

FIGURE 13

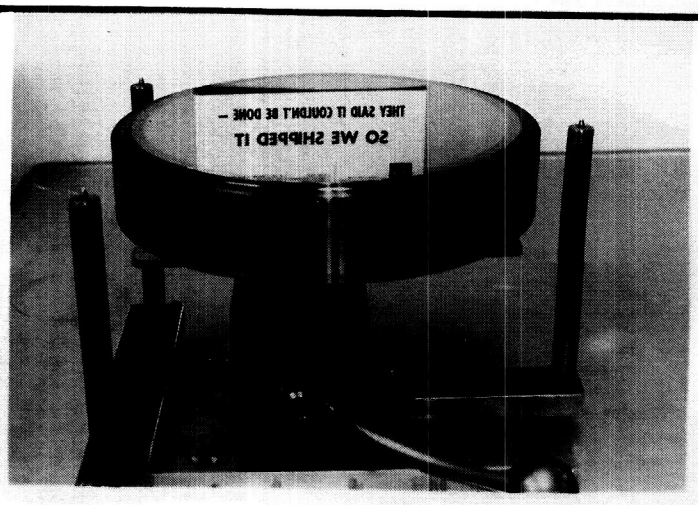

FIGURE 14

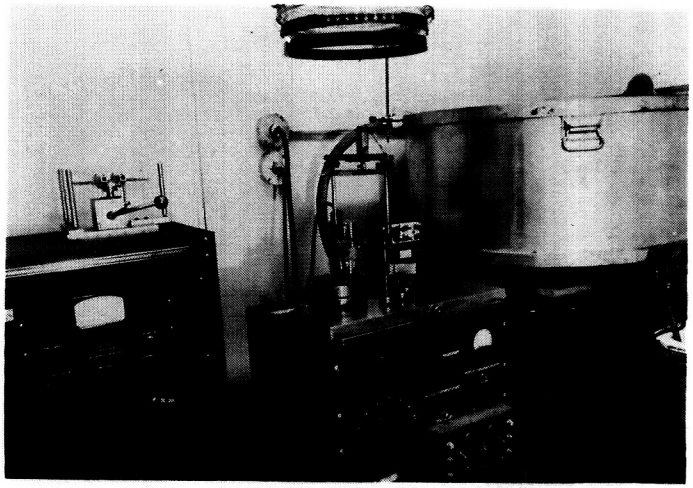

FIGURE 15

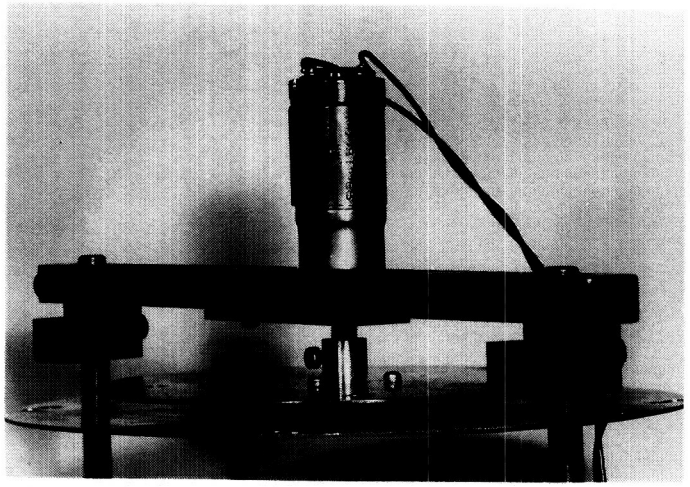

FIGURE 16

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CAST COLLODION MEMBRANE DIAMETER VS.
VOLUME OF MEMBRANE CASTING SOLUTION

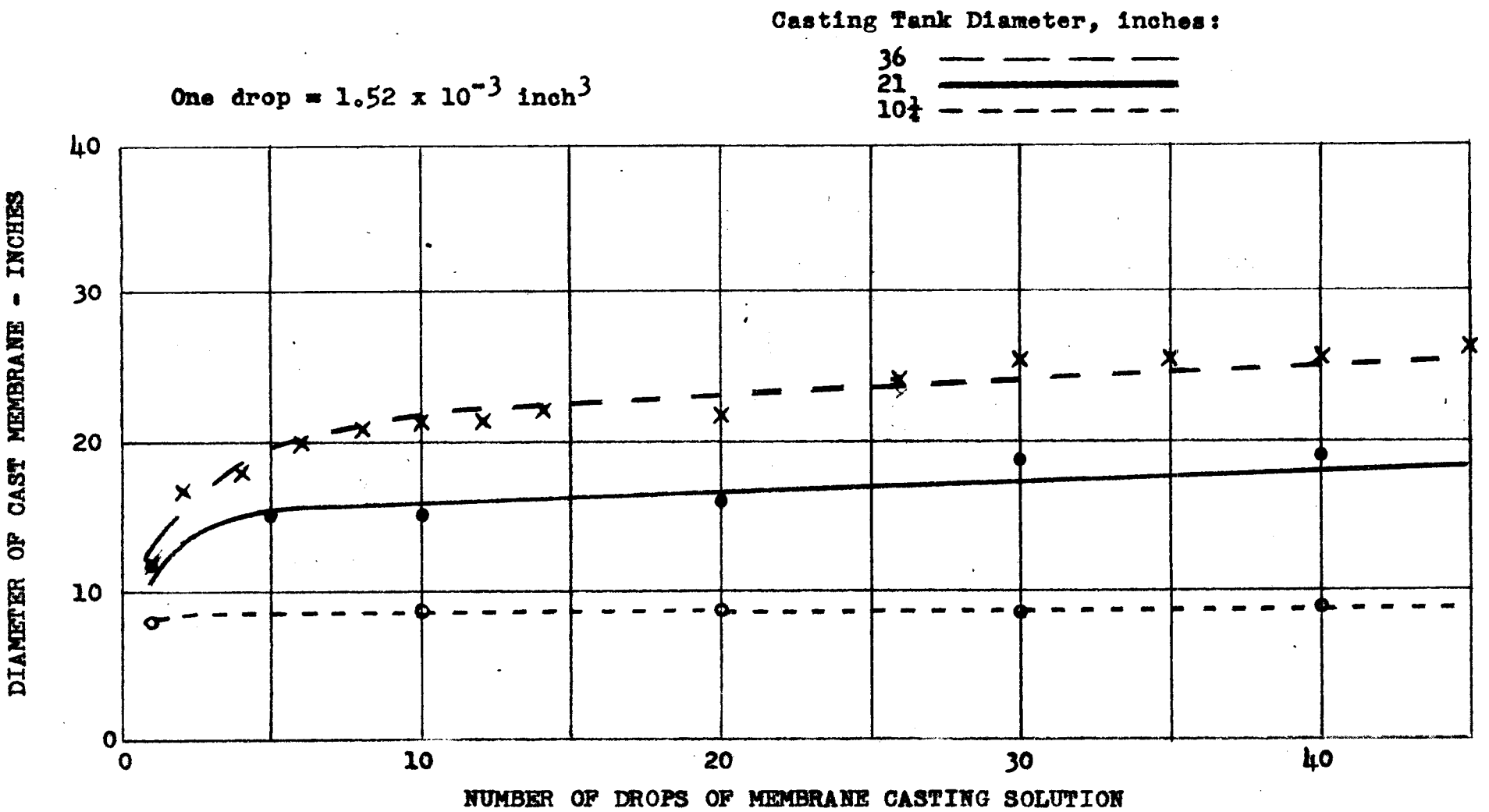

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FIGURE 17

DRY THICKNESS OF CAST COLLODION MEMBRANE
VS. VOLUME OF MEMBRANE CASTING SOLUTION

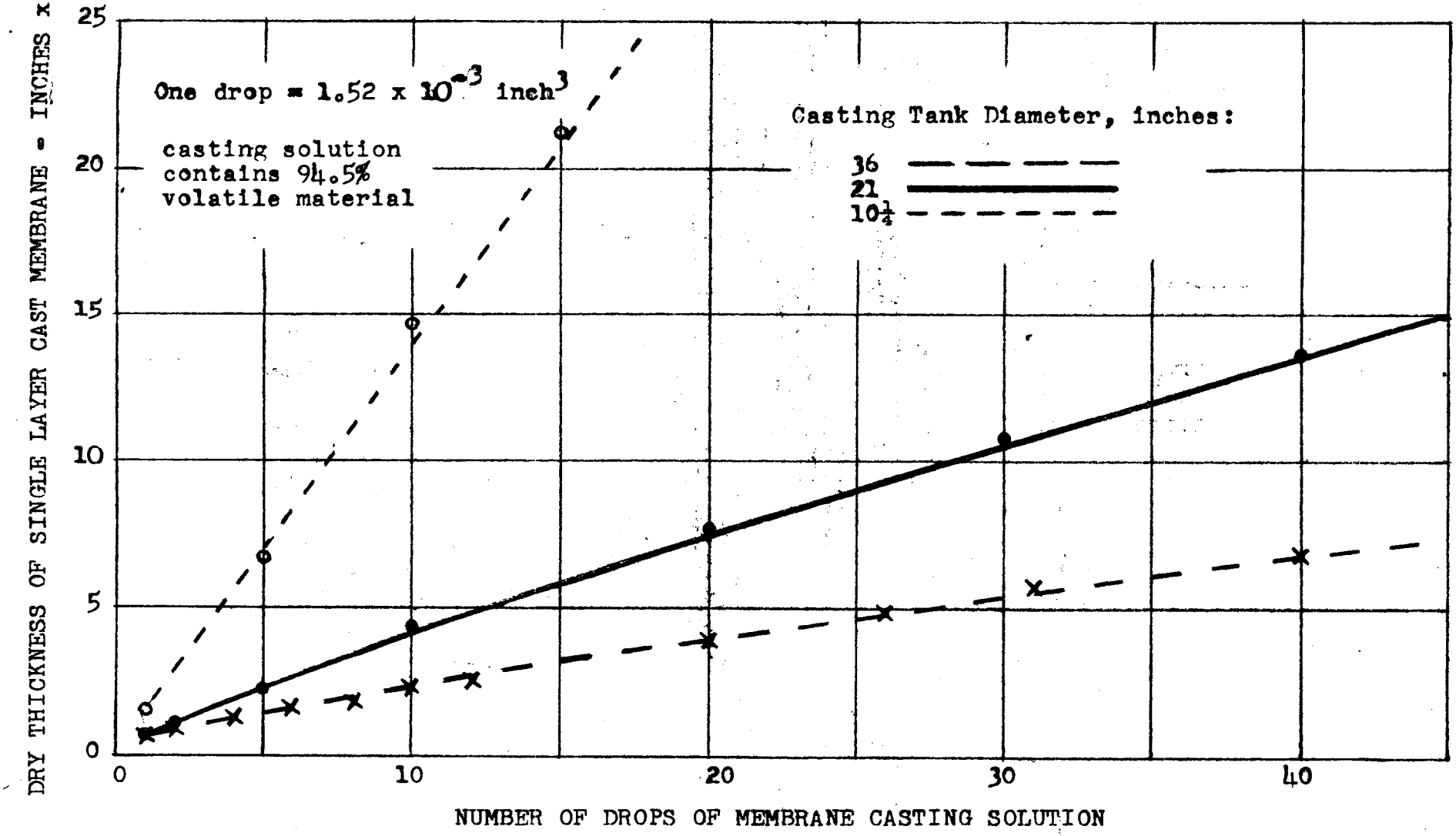

FIGURE 18

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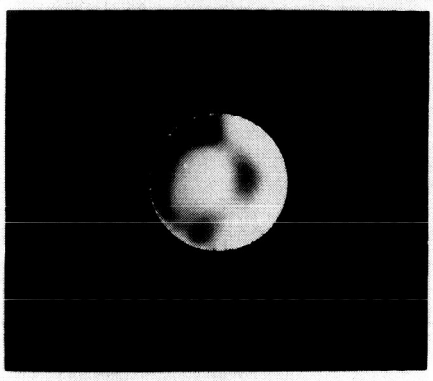


FIGURE 19

FIGURE 20

FIGURE 21

FIGURE 22

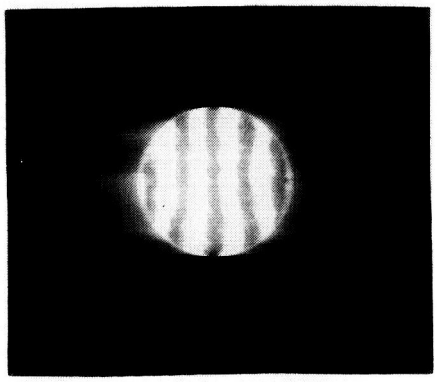


FIGURE 23

the membrane which self-adhered to it in less than one second. Precautions were taken to have the laboratory humidity condition uniform and to avoid the breath of laboratory personnel from coming into contact with the membrane before it adhered to the support ring. No membranes were applied in humidities below 30%.

4. METAL-COATING OF CAST COLLODION MEMBRANES

a. Previous work in connection with infrared detectors required both metallic gold and gold-black to be deposited by evaporation upon thin collodion membranes. Since the laboratory set-ups were readily available at the time this investigation began gold was used to provide the electrical conductivity and optical reflectivity necessary to test collodion membrane mirrors using electrostatic deflection. However, many other metals could have been used in lieu of gold or could have been deposited over the gold coatings to obtain better reflectivity in the blue and ultra-violet regions.

b. At the beginning of this investigation collodion membrane mirrors were originally coated with the hot gold source and mirror in fixed positions. This method of evaporation resulted in very poor figure-of-revolution accuracy under electrostatic deflection. Since it was previously known that when most metals are evaporated upon a thin collodion membrane the stiffness of the membrane is increased it was assumed that the poor figure-of-revolution accuracy was due to irregularities in the thickness of evaporated gold. Accordingly, the precision steel membrane support

rings were screwed to the motor-driven disc shown in Figure 16 which rotated at 25 RPM during evaporation. The membrane side of the ring faced downward. The stationary gold-heating filament was located approximately 2 inches from the rotational axis approximately 4 inches below the membrane surface. This method of evaporation resulted in back-coated rather than first surface membrane mirrors. This method of coating was selected merely because it permitted the support rings to be more easily mounted on the rotary evaporation support. The heater was adjusted to evaporate gold at 1 micron pressure at a slow rate over a period of 10 minutes or 250 revolutions. As a further step to insure maximum figure-of-revolution uniformity the gold heater filament temperature was slowly raised to its working temperature over a period of about one minute and slowly lowered at the same rate. Usually two such coatings were applied to obtain a gold coating that appeared dark green by transmitted light.

c. Due to rotation of the membrane during evaporation this procedure produced extremely uniform circumferential distribution of the gold coating on the membrane. However, the radial distribution of the gold was found to be less concentrated at the periphery than at the center. When electrostatic deflection was applied the resulting optical figure of the coated membrane was a highly accurate figure-of-revolution of the form generally referred to as an oblate sphere. The longer radius of

curvature at the center of this figure was due to the greater thickness of gold deposition at the center which caused the membrane stiffness to be greater at the center.

d. Such deviations of the figure-of-revolution from a sphere or parabola can be corrected at a later stage of this development when the necessary time is available to determine the location of the gold or other metal source which will produce the proper radial distribution of the metal coating. It is important to note that control of the radial distribution of the evaporated metal coating offers an accurate "fine-adjustment" means for obtaining any desired aspheric or spherical figure of membrane mirrors. This control may be accomplished by varying the position of the gold source from the rotational axis or by interposing a properly-curved aperture between the gold source and the membrane.

5. EFFORTS TO PRODUCE THICKER CAST COLLODION MEMBRANES

a. The type of collodion membranes described above under Section 3. were selected for use after a brief intensive attempt to produce substantially thicker membranes. This brief effort revealed that the development of substantially thicker than 10×10^{-6} inch cast membranes might require more time than was available for the complete investigation of feasibility of membrane mirrors. When this possibility became apparent it was decided to investigate and demonstrate the feasibility of precision membrane mirrors using the thinner membranes which had already been developed and found to be highly satisfactory

except for their thinness.

b. Efforts to produce thicker cast membranes proceeded in two directions as follows:

(1) Multiple ply membranes were produced by allowing one or more membranes of the type described under Section 3. to fold over the first double membrane on the removal card. The original double membrane and each additional double membrane deposited over it was baked for approximately 30 minutes at 95°C before the next double membrane was deposited. To compensate any small variations in the thickness of each membrane the second membrane was deposited with the removal card rotated 180° from its original position in the casting tank. The third membrane was deposited with the removal card 90° from its original position. The fourth membrane (actually the seventh and eighth single membranes) was also deposited with the removal card 90° from its original position but in the 180° opposite direction. In this manner a relatively large number of membranes could be used. As many as four successive overlays (eight single membranes) were successfully produced but the total number feasible appears to be limited only by the degree of effort expended to avoid accidental flaws which require the multiple ply membrane to be discarded. No difficulty was encountered in applying four ply double membranes to the precision steel support rings provided that

application occurred within 5 minutes or less after removal from the water tank. Better adherence could be obtained when this time was reduced.

(2) Single ply membranes of substantially greater thickness were first attempted by merely utilizing a much larger amount of the film casting solution specified in Section 3. This resulted in thicker membranes but also large uniformity variations which were easily visible when observed by means of the schlieren test system. The resulting membranes also showed wide interference color variations while on the casting water surface after hardening. In an effort to improve the uniformity of thicker membranes the following "spot check" experiments were made to determine the influence of the following factors and to obtain a better knowledge of the phenomena involved in membrane casting:

(a) Laboratory air drafts. Experiments ranging from the use of a plate two inches above the casting water surface to eliminate room air drafts to the use of a fan blowing air over the tank at the rate of one to two feet/second resulted in no significant improvement or change in the degree of uniformity.

(b) Casting water circulation. Great care was exercised to minimize residual water currents by inserting metal baffles but no significant improvement resulted since the water was

usually allowed to become "quiet" for 15 - 30 minutes before casting a membrane.

(c) Casting water ripples and waves. Previous tests had shown that thinner optimum membranes could be cast consistently without difficulty provided that short wavelength ripples due to building vibrations were eliminated by mounting the casting tank on three foam rubber pads. The very low amplitude, long wavelength waves which were present 15 minutes after filling the tank were found to cause no difficulty when thinner membranes were cast. However, no improvement in the uniformity of thicker or thinner membranes was noted when the foam rubber shock mounts were made softer in order to reduce ripples and waves to a substantially greater degree.

(d) Amount of solvent in film casting solution. On the assumption that non-uniformities might be caused by local drying before the film solution had spread evenly over the water surface several times the proportion of n-amyl acetate specified in Section 3. was added in an effort to lengthen the time required for the membrane to harden. These experiments yielded no significant or consistent improvements in membrane uniformity.

(e) Variations in membrane casting solution ingredients. The proportions given in Section 3.

were varied and various solvents such as amyl acetate, benzyl acetate, alcohol, acetone, lacquer thinner, glyptal, and nitrobenzene were added to or substituted for the n-amyl acetate normally used. No significant improvement in uniformity was achieved.

(f) Casting water additives. Various materials such as aerosol, salt, sugar, gelatin, gum arabic, "glim", alcohol, glycerine and n-amyl acetate were added to the casting water with no significant improvement in uniformity. A small amount of gelatin appeared slightly beneficial, perhaps due to the damping of water currents caused by the increased viscosity of the gelatin-water mixture.

(g) Water temperature. Variation of the casting water temperature revealed that the most uniform membranes of all thicknesses were obtained for low water temperatures in the range 6° to 10°C, as supplied by New York City during the winter season. Warmer water presumably caused too high a rate of solvent evaporation. Due to the problem of cooling the tank water temperatures below 6°C were not tried. However, there appears to be no indication that membrane uniformity will be materially improved at lower water temperatures.

(h) Rate of applying film-casting solution to the water surface. Experience in the casting of membranes as outlined in Section 3. has shown that best results are obtained when the film casting solution is dropped on the casting water at the rate of approximately 4 drops/second with the dropper not more than 3/16 inch above the water. No improvement in the uniformity of thicker membranes could be achieved by varying this rate or by placing the dropper nearly in contact with the water surface in order to prevent the small ripples produced by the solvent drops.

(i) Dropping of the membrane casting solution from a multiplicity of nozzles. An experiment was run using seven eye-droppers to drop the casting solution on the water surface simultaneously. The droppers were located at the corners and center of a hexagon having 9 inch sides. While no improvement resulted in the uniformity of thicker membranes cast in the above manner the multiple dropping technique appears extremely promising as a means for casting membranes of the type described in Section 3. over very large areas when larger membranes are required. This method of casting and the thickness relationships shown in Figure 18 should be investigated more

thoroughly when work is again resumed on membrane mirrors.

(j) Quantity of casting solution vs. membrane diameter and thickness. Using the 36 inch diameter casting tank and auxiliary 21 and 10.25 inch diameter containers the relationship between the number of drops used to cast various collodion membranes and their diameters was obtained. This relationship is shown in Figure 17. From the above data the corresponding thicknesses of the liquid film casting solution immediately after being dropped upon the water surface were computed on the assumption that the liquid solution assumes very nearly uniform thickness before drying. Based upon the known fraction of volatile components in the casting solution the ratio of the dry volume of a cast collodion membrane to the original volume of the film-casting solution used was computed. Figure 18 was then prepared using this volume ratio and the wet thicknesses computed above. Using the 36 inch tank it will be seen from Figure 18 that the standard 26 drop membrane has a thickness of 4.9×10^{-6} inch. When folded over the removal card the resulting double membrane will have a thickness of approximately 9.8×10^{-6} inch. This is in excellent

agreement with the 10 x 10^{-6} inch round figure used for convenience throughout this report.

6. LAPPING OF MEMBRANE SUPPORT RINGS

a. Three 7 inch and two 4 inch diameter precision steel membrane support rings were turned from Ketos steel tube stock and hardened. The inside surface of the ring close to the precision flat surface was first highly polished using optical rouge on a wood stick. The precision flat surface of each ring was then ground flat successively against fine-ground glass laps using 4F Carborundum, 5 micron and 0 to 0.5 micron diamond dust respectively. Kerosene was used as a non-rusting vehicle for each of the above abrasives. By this means the inner edge was lapped "molecularly" sharp and turned-down edge was eliminated.

b. Three 26 inch diameter x 1 inch plate glass laps were prepared for the above precision ring grinding process by successively grinding each glass disc with another until all were flat. When flatness was achieved the surfaces were fine-ground using 4F Carborundum. Each glass tool was used with only one of the three grades of abrasives listed above.

c. Support rings were tested using an 8 inch diameter Pyrex test flat accurate to 1/20 wavelength. No great difficulty was experienced in lapping a 7 inch diameter support ring flat to within 1/20 wavelength within eight hours so that only a single interference color appeared around its inside edge when viewed through the test flat.

d. Only one out of 5 steel rings ground as described above did not remain flat. This spurious ring was cycled from cold to boiling water several times and relapped to 1/20 wavelength. It has shown no further departures from flat since being reworked.

7. TEST RESULTS USING COLLODION MEMBRANE MIRRORS

a. The first experiments conducted with the apparatus shown in Figure 1 utilized 7 inch diameter membranes produced as described under Section 3. The optical figures originally obtained using electrostatic deflection were far from accurate figures-of-revolution. This led to the procedure of rotating the mirror relative to the gold source during evaporation as described under Section 4.

b. While rotary evaporation eliminated nearly all random irregularities gross astigmatic errors still remained. It was suspected that these were due to gradual variations in the thickness or stiffness of the membrane across the removal card hole diameter. To investigate this condition two-ply and four-ply membranes were produced as described under Section 5. above in an effort to compensate such effects since, when a second membrane is cast over an original membrane, a thick region should, to a first order approximation, be compensated by a thin region. This would be true of the third and fourth membranes cast over the first and second. Unfortunately, such two and four ply membranes showed only slight improvement. In addition, a removal card was tried

having a square hole with sides equal to the diameter of the circular hole in the removal card shown in Figure 11. No uniformity improvement was noted using single ply membranes removed with this card. Based upon tests of three membranes made using the square hole it appears that the shape of the hole in the removal card is far from critical.

c. The flatness of the mirror membrane support rings were suspected and checked. It was found that one of the support rings had deviated about one wavelength from flat. This condition was easily corrected by regrinding the ring on the 0 to 0.5 micron glass lap. The other rings were found to be still flat to about 1/20 wavelength. Subsequently, all precision rings were checked for flatness prior to applying each new membrane for test. It was not found necessary to re-lap a ring for any other reason than to restore a sharp inner edge. The "molecularly" sharp edges were often dulled by the most gentle use of lens or "Kleenex" tissue. No significant improvement in figure-of-revolution uniformity resulted from these changes.

d. The flatness of the aluminum electrode plate was suspected and checked by turning it to its four 90° mounting positions relative to the membrane when electrostatically deflected. Corresponding rotation of the distortion pattern as viewed via the schlieren system proved that it had warped. It was then reground flat to within approximately 0.0001 inch against a flat glass

plate using 4F Carborundum. When again tested by rotation the electrode caused no observable change in the knife-edge shadows. Subsequently, similar checks were made by rotating the electrode when each new membrane was tested but it was not found necessary to regrind it. While correction of the electrode errors resulted in some improvement of figure-of-revolution uniformity variations in the order of one to two wavelengths still persisted.

e. On one occasion the rubber gasket shown on Figure 1 between support ring 9 and support plate 7 was too tightly compressed and caused distortion of the support ring and membrane which could be eliminated when the gasket compression was reduced. To eliminate any possibility of recurrence of this distortion the solid rubber gasket was replaced by four softer foam rubber washers at each of the four mounting screw positions.

f. It was next assumed that the uniformity difficulties might be due to the fact that the diameter of the piece of collodion membrane used was only 9 inches while the diameter of the membrane mirror was 7 inches, or nearly as large. It was thought that the 9 inch diameter membrane might be sufficiently uniform over only a central area, perhaps half its full diameter. Therefore, two 4 inch diameter Ketos steel membrane support rings were quickly made and tests resumed with the apparatus modified as shown in Figure 1. These tests showed some slight improvement but figure-of-revolution accuracy was still

far from acceptable.

g. It is important to note that when the above experiments were made the stretching procedure described above under 3.c. was employed. However, after the first tests of the 4 inch diameter rings yielded only slight improvement it was decided to delete the stretching procedure and to use greater care in transferring the membrane to the 4 inch diameter support ring. Precautions were also taken to prevent humidity variations over the membrane by exercising care to avoid the breath of the person performing the work from blowing close to the membrane. A silica gel dryer package was also fastened inside the metal spacer plate 8 shown in Figure 1. When these changes were made a very great improvement in uniformity was achieved using an optimum single ply membrane of the type described under 3.a., 3.b., and 3.e. above. Its optical figure is discussed in detail below.

h. Figure 19 shows a typical shadow pattern as obtained for a gold-coated 4 inch diameter single ply membrane mirror with the above improvements. A deflection voltage of 4900 volts and an electrode spacing of 0.4 inch produced an average test radius of 86 inches. The focal lead screw and a calibrated vernier control in the high voltage supply circuit were both used to determine the difference between the radius of curvature at the outer edge and at the center of the membrane. The mechanical and electrical methods of overall radius variation measurement

checked each other within less than 5%. These measurements revealed that the radius of curvature was 0.21 inch longer at the center than at the edge. This meant that the general mirror figure was an oblate spheroid. When both the pinhole and knife-edge move together the radius of curvature variation C for a parabolic mirror is $r^2/2R$ where r is the mirror radius and R is its average radius of curvature. Using this relation we obtain the figure 0.023 inch for C. Therefore, the membrane mirror had a variation of radius of curvature approximately .21/.023 or 9.1 times greater than for a parabolic mirror of the same average radius of curvature and diameter. The maximum deviation D of a parabola from the nearest average circle is very close to $\frac{r^4}{24R^3}$. Using this relation for a 4 inch diameter mirror of 86 inch average radius we find that D equals 1.05×10^{-6} inch. Since the membrane mirror figure had 9.1 times the curvature variation of a parabola its maximum deviation from an average sphere was approximately $9.1 \times 1.05 \times 10^{-6}$ or 9.5×10^{-6} inch. Using the calibrated voltage controls it was observed that the maximum irregularity of the knife-edge pattern (as shown in Figure 19) could be compensated by a 0.03 inch change in the radial adjustment of the pinhole and knife-edge assembly. Therefore, the maximum irregularity (deviation from a perfect figure-of-revolution) was $\frac{.03}{.21} \times 9.5 \times 10^{-6}$ or 1.36×10^{-6}. The round number 1.5×10^{-6} inch

is therefore given as the order of accuracy of the 4 inch diameter collodion mirror.

i. Since the contract funds were nearly expended at this point no time was available to run more than one other test similar to the above or to re-check larger 7 inch diameter or double-ply membranes using the revised procedures outlined under 7.g. above. In the short time which remained it was considered important to investigate commercially-available membranes as described below under Section 8.

j. It is important to note that when collodion mirrors were not deflected they were exceedingly good flats having a "perfect" polish, no small surface irregularities, and general accuracy as high as that of their metal support rings which was 1/20 wavelength (1×10^{-6} inch) or better.

k. Due to their thinness all collodion membranes vibrated noticeably in response to shock impulses. However, the amplitude and duration of such vibrations was much less for 4-ply than for single-ply membranes.

l. The high voltage supply shown in Figure 2 worked exceedingly well and permitted the very fine vernier adjustments of membrane radius needed for schlieren observations to be made with ease. No difficulty was experienced due to voltage drift.

8. TEST RESULTS USING COMMERCIALLY-AVAILABLE PLASTIC MEMBRANES

a. The apparatus shown in Figure 3 was first set up using Du Pont Teslar 0.0005 inch thick with no metal coating applied. Deflections of the membrane were produced by

means of the apparatus shown in Figure 4. It was found that the membrane tension could be adjusted very easily by means of the 40 set screws. The first accurate average spherical figure was achieved after approximately 8 hours during which the knife-edge shadows were viewed by one man while a second man adjusted the set screws as specified by the first man.

b. Figure 20 shows a typical schlieren knife-edge test pattern for an uncoated Du Pont Teslar membrane 0.0005 inch thick when deflected to an 86 inch radius of curvature. Since the membrane had no metal coating the shadow patterns represent the combined irregularities of both surfaces. These combined irregularities were estimated to be in the order of 10×10^{-6} inch and are clearly visible in Figure 20. This material also has an undesirable turbid characteristic which reduces the shadow contrasts.

c. Figures 21, 22, and 23 show a schlieren knife-edge test pattern and single and multiple line Ronchi grid test patterns, respectively, for a Du Pont Type C Mylar membrane 0.00025 inch thick and gold-coated upon its first surface when deflected to an 86 inch radius of curvature. It may be noted that Type C Mylar shows excellent shadow contrasts when viewed by schlieren knife-edge and produces negligible scatter due to turbidity. It was estimated that the local irregularities shown represent surface variations in the range from 0 to 5×10^{-6} inch. The poorer contrast of the Ronchi patterns is due to

diffraction effects caused by the grid.

d. After experience totaling approximately three days a team of two men could adjust a Type C Mylar membrane to within 5×10^{-6} inch or less from spherical (except for the small uncompensatable local irregularities) within about three hours. It was found that the initial coarse adjustments could be made most rapidly using Ronchi viewing adjusted to show two to four lines. Future adjustments of this type might be further simplified by using a pair of 90° crossed grids instead of a single grid so that the errors in mirror figure may be observed simultaneously along two axes. Fine adjustments were more easily made using simple schlieren knife-edge viewing of the mirror figure.

e. The suction apparatus shown in Figure 4 worked exceedingly well and permitted the very fine vernier adjustments of membrane radius needed for schlieren or Ronchi observations to be made with ease.

f. While the above surface irregularities are large it is interesting to compare them with the knife-edge test patterns obtained with the 200 inch mirror of the Hale telescope at Mount Palomar Observatory. (1) The 200 inch mirror knife-edge patterns appear to show small

(1) Final adjustments and tests of the Hale telescope, Publications of the Astronomical Society of the Pacific, 1950, Vol. 62, Pages 91 - 97.

local surface irregularities comparable to those which appear in Figure 21. This suggests an interesting question: How closely would a 200 inch Type C Mylar membrane mirror compare with the actual 200 inch ribbed pyrex mirror?

g. Due to its great thickness and surface tension the 4 inch diameter Mylar membrane mirror showed negligible vibrational response to gentle tapping of the support structure with a metal tool. Apparently, shock-excited vibrations are damped out within a fraction of a second.

9. CONCLUSIONS

a. Cast Collodion Membrane Mirrors

(1) Cast collodion double membranes in the order of 10×10^{-6} inch thickness can be produced having negligible local surface irregularities and a "polish" equivalent to the most perfectly polished glass optical surface. This "polish" is not degenerated by evaporation of gold upon its surface. These membranes possess sufficient thickness and stiffness uniformity to permit figure-of-revolution accuracies of at least 1.5×10^{-6} inch to be obtained when a single ply membrane is adhered to a 4 inch diameter precision steel ring which is flat to 1×10^{-6} inch. This accuracy may be obtained after evaporation with gold and using electrostatic deflection.

(2) Since little time was available for further refinements and tests after high accuracy was finally

achieved it is probable that the 1.5×10^{-6} inch accuracy figure obtained can be improved significantly and that much larger mirrors can be produced having good accuracy.

(3) The stiffness of a cast collodion membrane is increased by deposition of gold and many other metals upon it. It is therefore necessary to rotate a cast collodion membrane about its intended optical axis during evaporation of the metal in order to obtain an accurate figure-of-revolution. By controlling the radial distribution of the metal during evaporation it should be possible to obtain fine control of the figure of a membrane mirror.

(4) Control of the position and size of a flat electrode and its potential difference relative to the membrane will provide control of the figure of a membrane mirror over a wider range. The electrode may also be curved in order to achieve control of the mirror figure. The edge-to-edge surface accuracy of the electrode can be at least 10 times poorer than that desired of the membrane mirror and the electrode does not need to be polished. Only a relatively coarse ground surface is necessary. Electrode accuracy becomes less critical as its size decreases and as its spacing increases relative to the membrane.

(5) Both 4 inch and 7 inch diameter precision steel membrane support rings can be lapped flat to within

1×10^{-6} inch in approximately one day.

(6) Multiple-ply double collodion membranes can be successfully produced up to at least 4-ply double membranes.

(7) One to four ply double collodion membranes adhere without difficulty upon contact with a clean, polished steel membrane support ring within less than one second. Experience obtained prior to this investigation has proven that collodion membranes adhere even more firmly to polished glass or ceramic surfaces.

(8) Membranes must be adhered to their precision support rings in a draft-free atmosphere of uniform humidity, preferably over 30%.

(9) Based upon experience using from one to four ply double membranes it should be possible to produce at least 10 to 20 ply double collodion membranes (100 to 200 $\times 10^{-6}$ inch thick). If difficulty is experienced in obtaining contact adherence of such thick membranes they can be utilized in the same manner as commercially-available membranes such as Du Pont Mylar.

(10) Due to their extreme thinness single-ply double collodion membranes are very sensitive to vibration. However, if their thickness is increased, as in the case of 4-ply double membranes, the effect of vibration is reduced very significantly. When 10 and 20 ply double membranes become available the effect of vibration will probably be negligible, as in the case of the commercial membranes.

(11) To prevent distortion of the optical figure great care must be exercised to prevent vertical, lateral, or rotational displacement of a collodion membrane relative to its precision support ring at the time adherence occurs. Membranes must be transferred directly to their support rings without previous mechanical stretching. When used in vacuum or in air at any constant humidity the optical figure of a collodion membrane mirror will not vary.

(12) The optical damage caused by accidental small perforations of the membrane covers an area approximately five times the diameter of the actual perforations. This offers a clue as to the order of damage which will be produced by meteorites.

b. Commercially-Available Plastic Membrane Mirrors

(1) A very satisfactory means for adjusting the radial tension of commercially-available membranes at 40 points around the mirror circumference has been developed. With it gold-coated membrane mirrors can be adjusted by two men to an average spherical figure within approximately 5×10^{-6} inch within a few hours. If more time is devoted to adjustment it should be possible to achieve 1×10^{-6} inch uniformity or better. However, due to surface irregularities of the plastic materials tested closer adjustments were not attempted. Once adjusted to a desired figure this type of membrane mirror appears to retain its optical figure

indefinitely.

(2) Only 0.0005 inch thick Du Pont Teslar and 0.00025 inch Du Pont Type C Mylar were tested. Teslar produces a prohibitive amount of light scatter due to a turbid surface condition and therefore is not satisfactory for optical purposes. Type C Mylar possesses a "highly-polished" optical surface which produces negligible light scatter. However, it does possess small local surface irregularities estimated to range from 0 to 5×10^{-6} inch. For precision optical purposes these surface irregularities must be reduced by approximately one order of magnitude.

(3) The vibrational response of a 4 inch diameter Mylar membrane mirror to shock excitation is negligible and is damped out within less than one second.

c. The results of this brief investigation are considered highly promising. At the present stage of investigation the membrane method appears to offer a potentially far less expensive and lower weight method of construction of large mirrors (36 inches and larger) than the use of solid glass or ceramic materials. The membrane method appears to offer the only practical means for constructing very large mirrors for space use (70 inches and larger).

10. RECOMMENDATIONS

a. As indicated above it has been concluded that cast collodion membrane mirrors can be made to accuracies

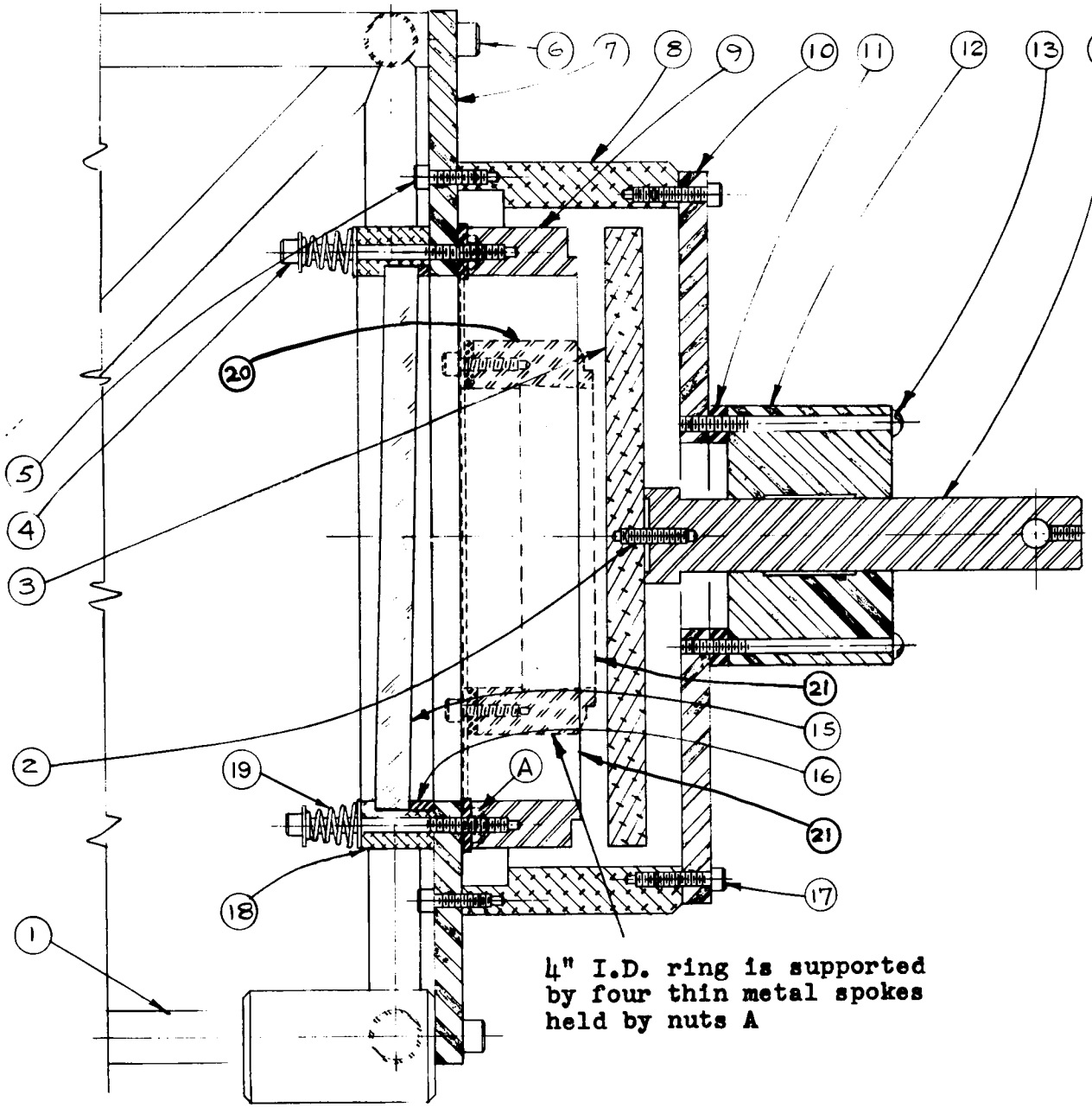
sufficiently high for astronomical use in space. However, since favorable experimental results with small test mirrors were obtained only a very short period prior to the time that the contract funds became exhausted their ultimate limitations were not determined. It is therefore recommended that:

(1) Apparatus and techniques for utilizing laboratory-cast and commercially-available membranes should be further refined so that their accuracy, thickness, and environmental limitations can be more precisely determined. All potentially useful commercially-available plastic films should be investigated. These experiments could be conducted using the present 4 inch and 7 inch mirror test apparatus now available.

(2) Since thicker, commercially-available membranes now appear feasible for precision optical use provided their surface accuracy can be improved by about one order of magnitude it is recommended that a prototype membrane objective mirror in the 24 to 36 inch diameter size range capable of utilizing Du Pont Type C Mylar and similar materials now be attempted. Such a larger mirror, when successfully developed, would provide a firm justification for the development of much thicker, multiple-ply cast collodion membranes or for the cost of development of thin plastic films of greater surface smoothness by one or more of the large plastic manufacturers.

(3) Small diameter collodion membrane mirrors cast in our laboratory have already proven capable of providing optical surfaces of astronomical quality and offer the most certain means for constructing large astronomical mirrors within the shortest period of time. Therefore, it is recommended that a prototype membrane mirror of the laboratory cast type having a diameter in the range from 24 to 36 inches and an accurate parabolic figure be attempted. Such a larger mirror, when successfully developed, would permit the design and construction of evaluation models for space use to be undertaken.

APPARATUS FOR TESTING CAST COLLODION
MEMBRANES WITH MEANS FOR ELECTROSTATIC DEFLECTION



Principal Parts

3 - Electrode disc

7 - Texolite support plate

8 - Metal spacer plate

9 - 7" I.D. Steel support ring

10 - Texolite support plate

11 - Rubber compression washer

12 - Nylon insulating bushing

13 - Electrode parallelism adjustment screws

14 - Metal electrode support

15 - Glass anti-draft window

20 - 4" I.D. Steel support ring (when used)

21 - Collodion membrane

FIGURE 1

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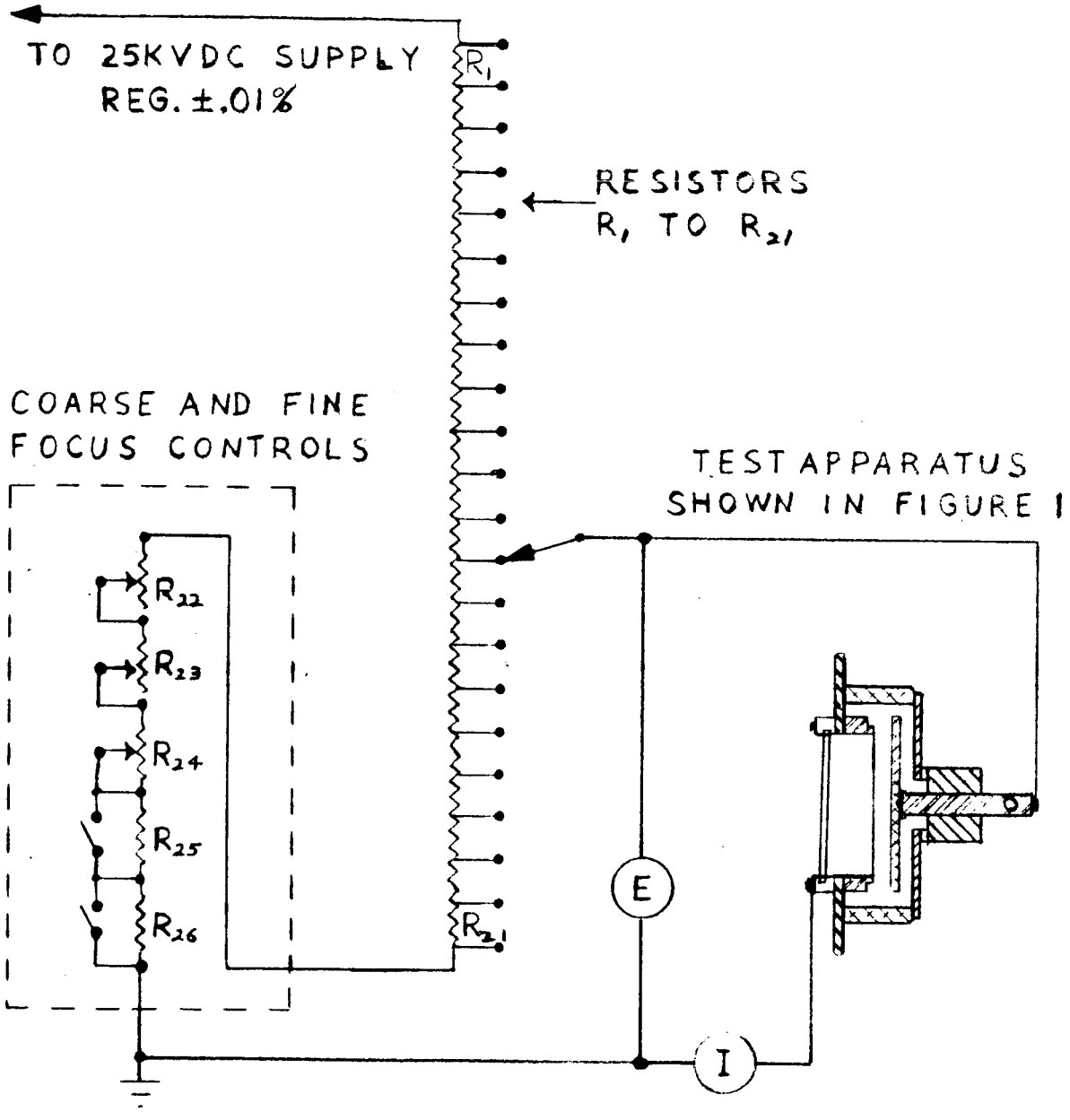
HIGH VOLTAGE SUPPLY FOR DEFLECTING CAST COLLODION MEMBRANES



R_1 TO R_{21}	22	MEG. OHM EACH
R_{22} AND R_{23}	3	" " "
R_{24}	7.5	" "
R_{25}	3	" "
R_{26}	22	" "

FIGURE 2

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APPARATUS FOR TESTING
COMMERCIALLY AVAILABLE MEMBRANES WITH
MEANS FOR ADJUSTMENT OF RADIAL TENSION

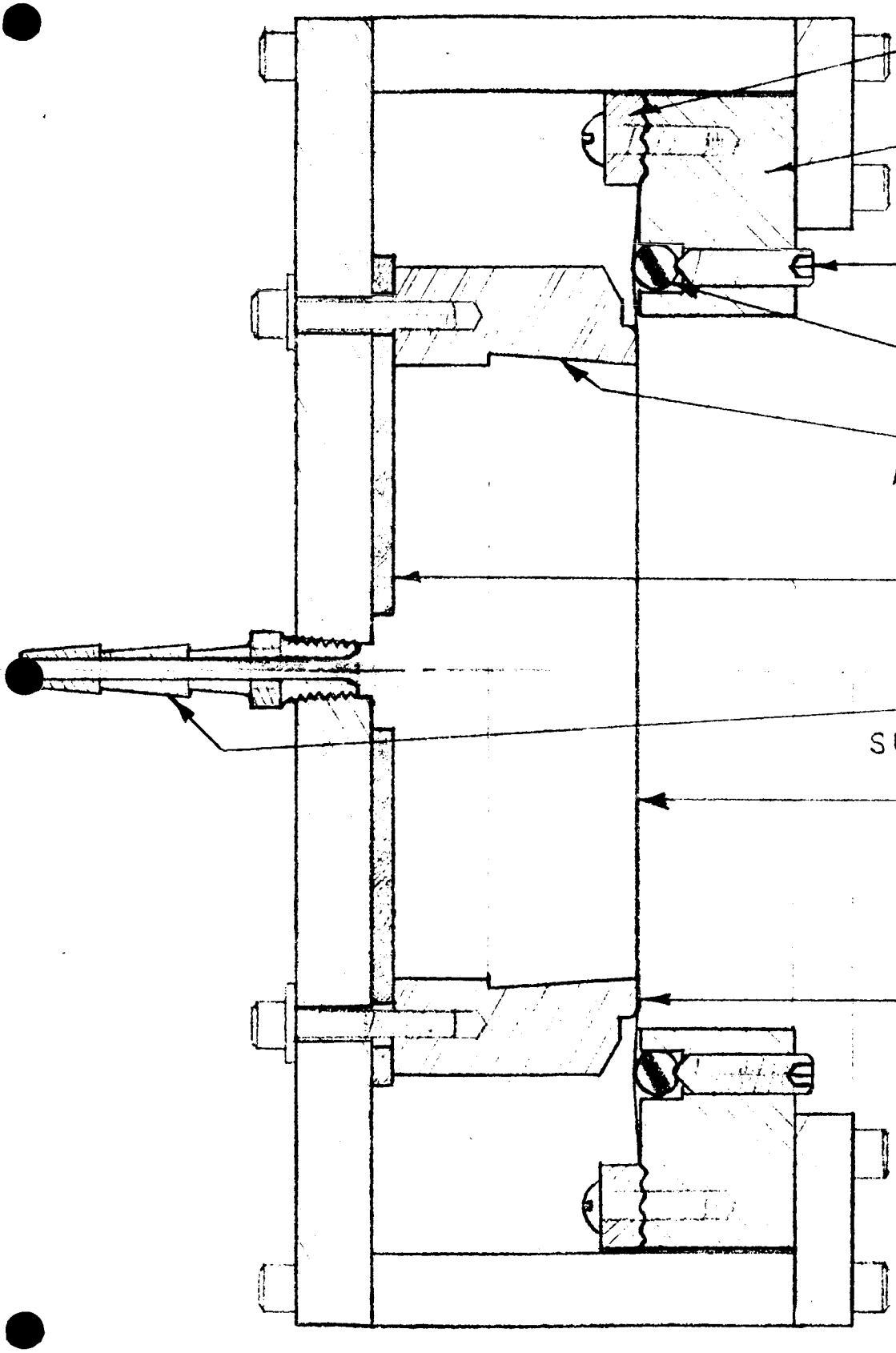
MEMBRANE CLAMP RING
SUPPORT RING CONTAINING 40 ADJUSTING SCREWS
"O" RING TENSION ADJUSTMENT SCREW
"O" RING (NEOPRENE)
PRECISION MEMBRANE SUPPORT RING 4" I.D.
GASKET SEAL FOR SUCTION TEST
CONNECTION TO SUCTION APPARATUS
TESLAR, MYLAR OR SIMILAR MEMBRANE 0.00025" TO 0.00050" THICK
THIS SURFACE LAPPED FLAT TO 1 X 10⁻⁶ INCH

FIGURE 3

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VACUUM GENERATING APPARATUS FOR DEFLECTING
COMMERCIALLY AVAILABLE MEMBRANES

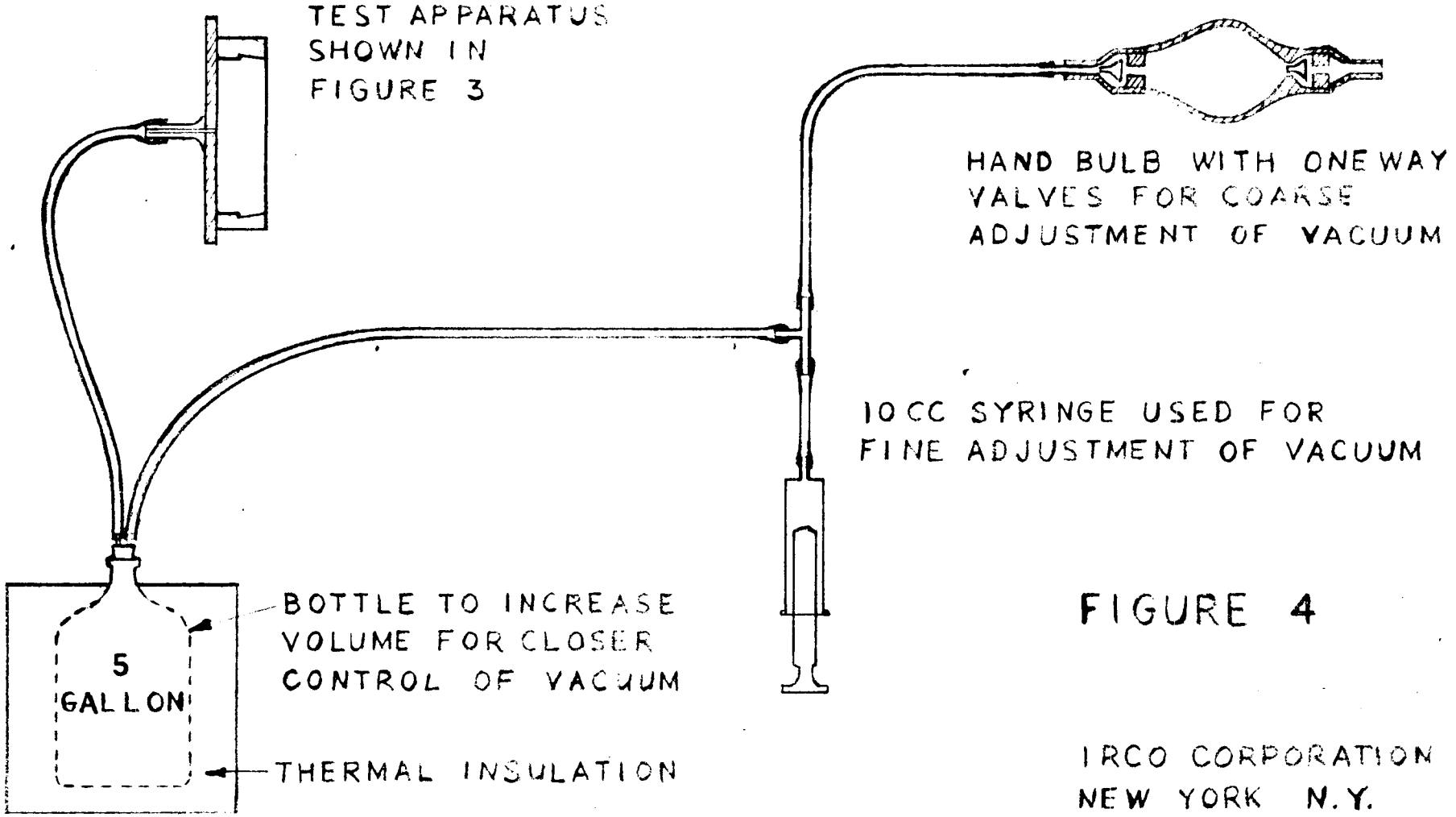

FIGURE 4

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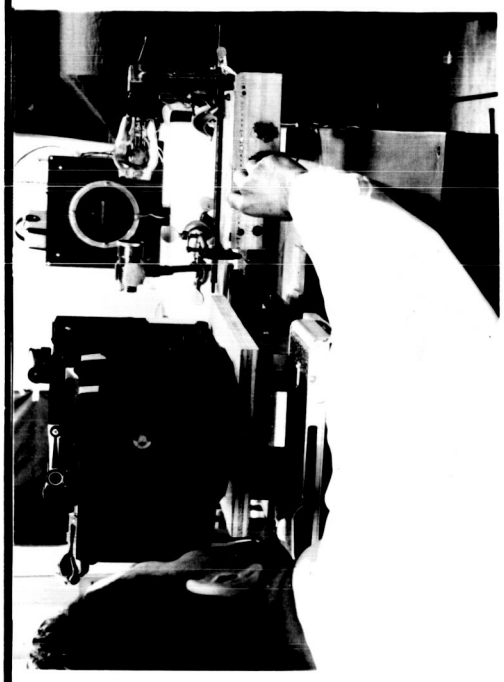

FIGURE 6

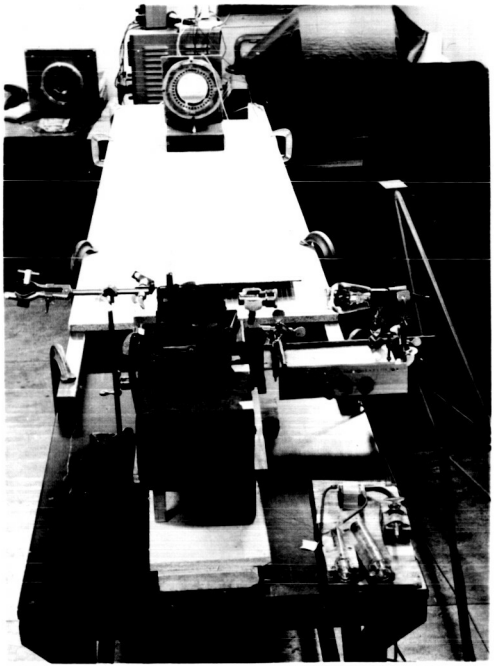

FIGURE 8

FIGURE 5

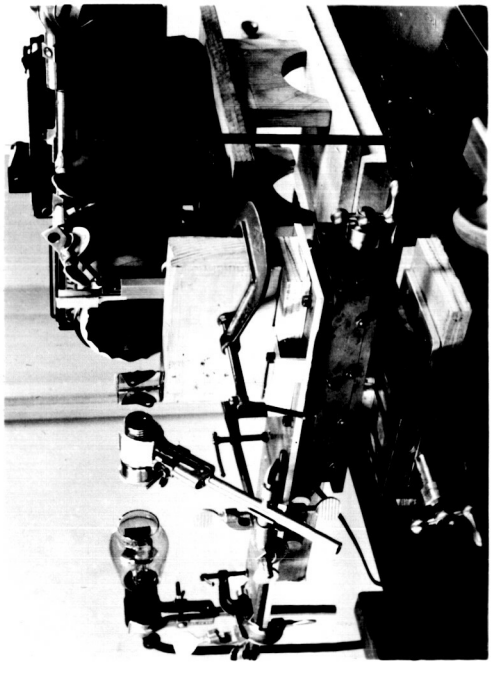

FIGURE 7

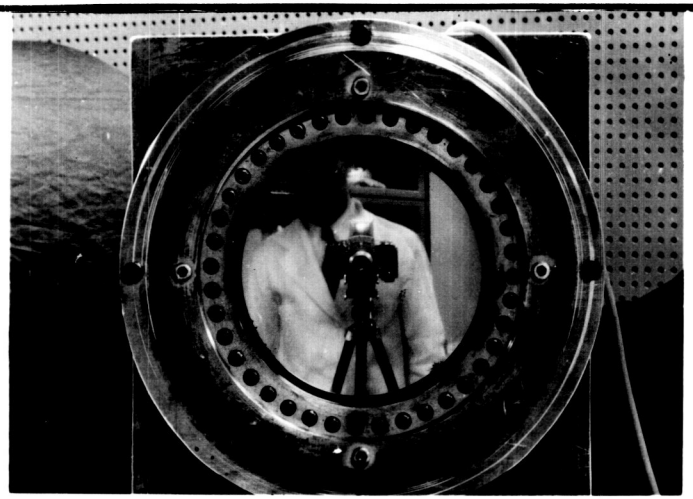

FIGURE 9

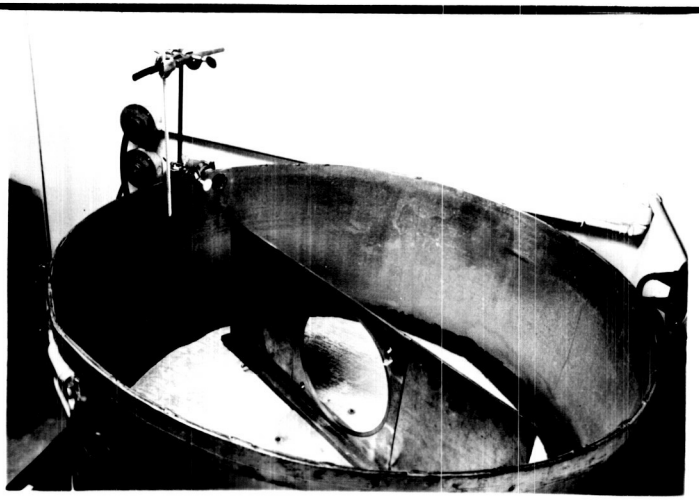

FIGURE 10

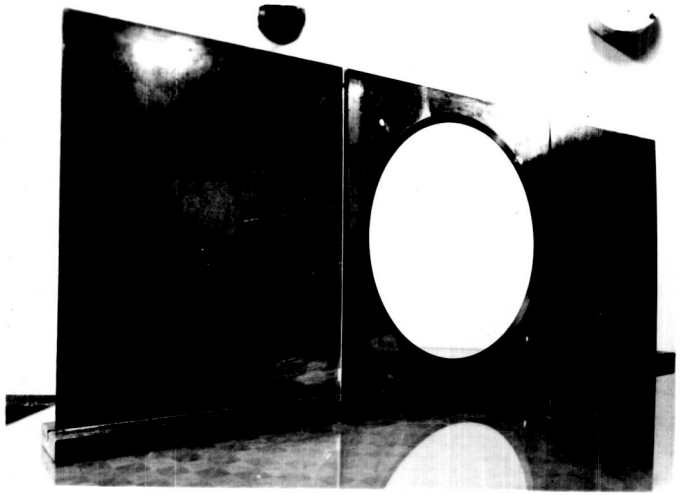

FIGURE 11

FIGURE 12

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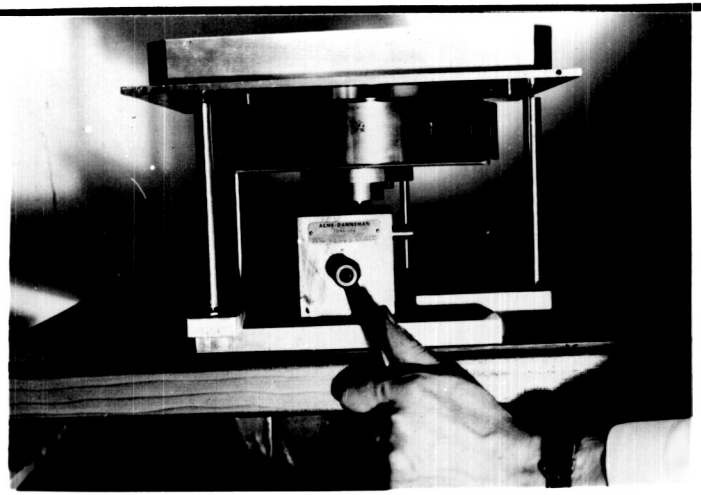

FIGURE 13

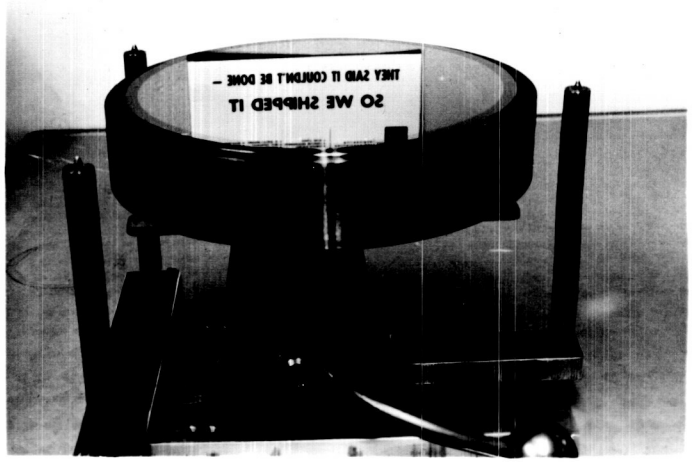

FIGURE 14

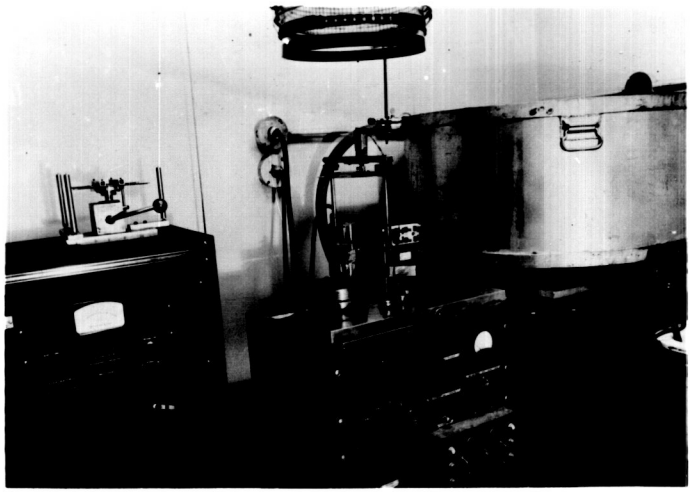

FIGURE 15

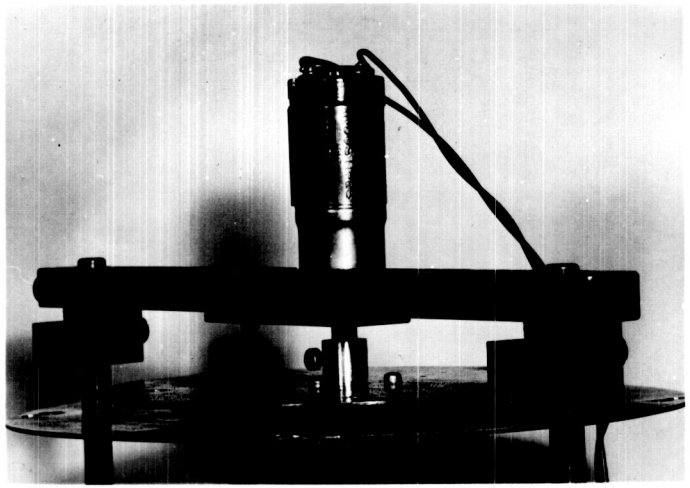

FIGURE 16

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CAST COLLODION MEMBRANE DIAMETER VS.
VOLUME OF MEMBRANE CASTING SOLUTION

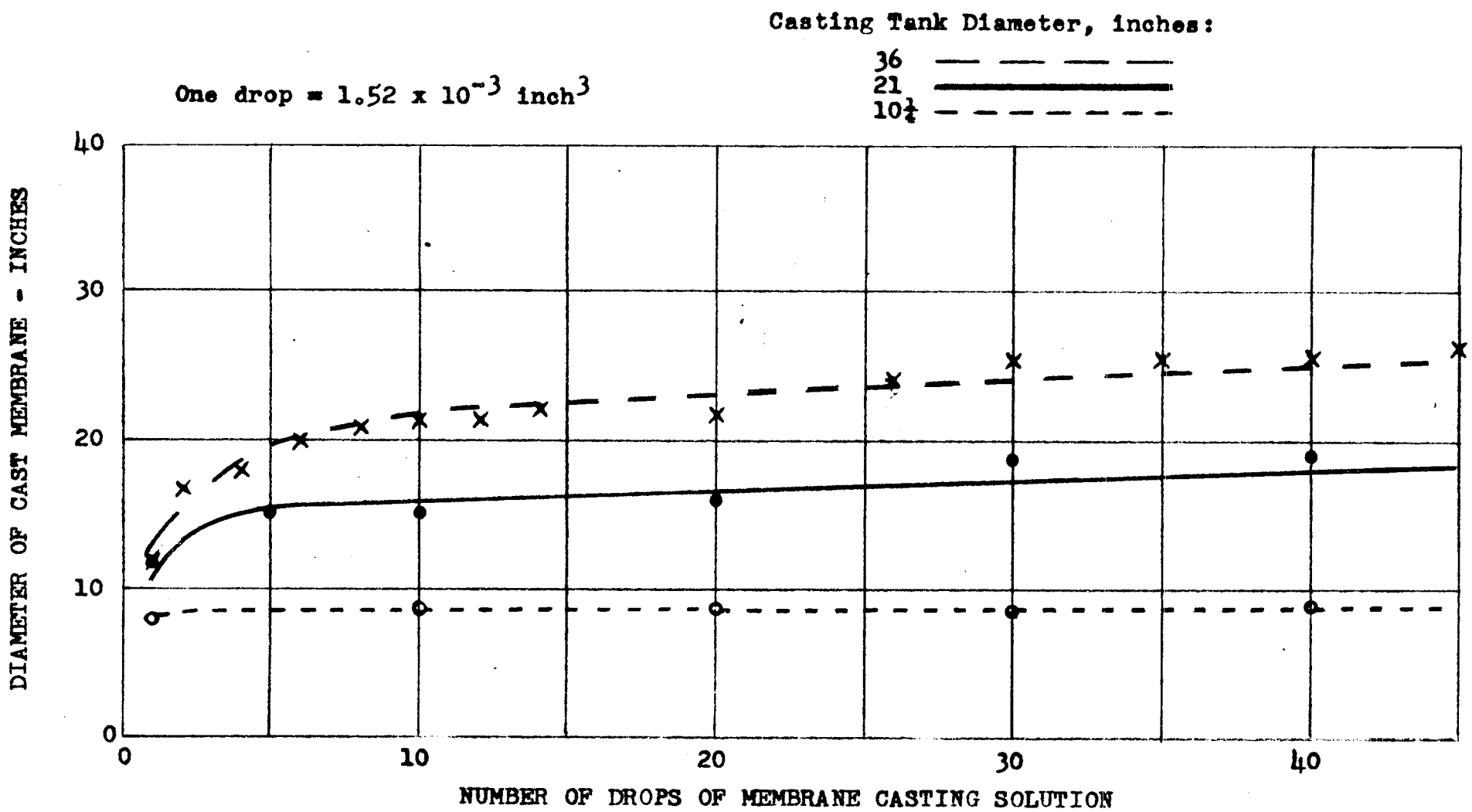

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FIGURE 17

DRY THICKNESS OF CAST COLLODION MEMBRANE
VS. VOLUME OF MEMBRANE CASTING SOLUTION

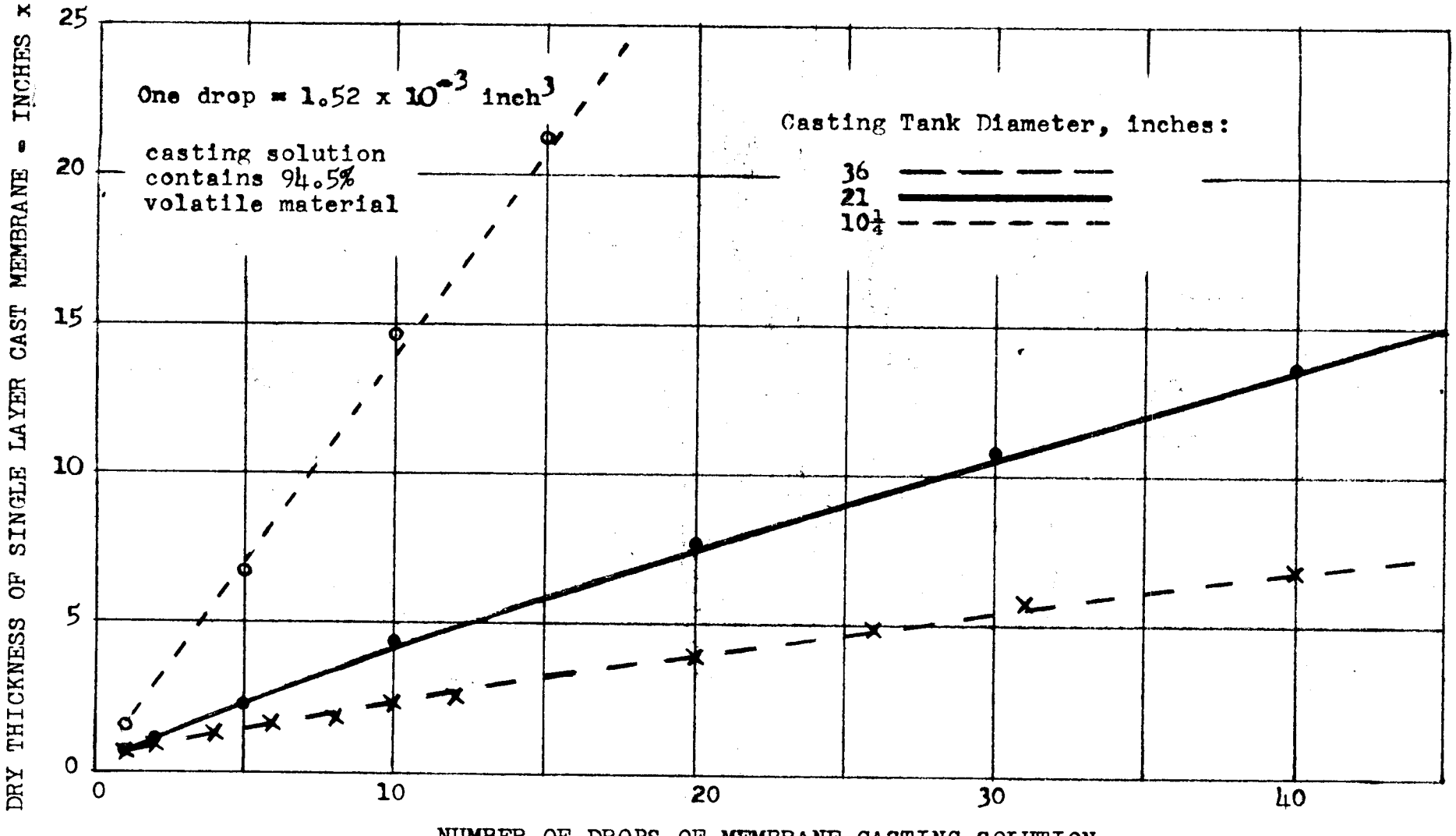

FIGURE 18

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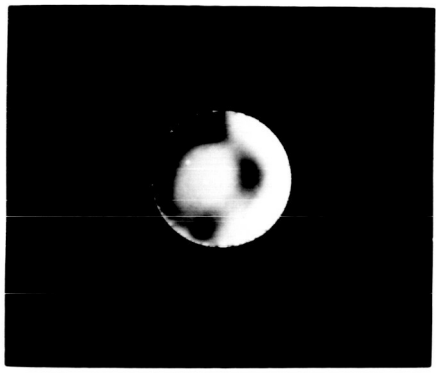

FIGURE 19

FIGURE 20

FIGURE 21

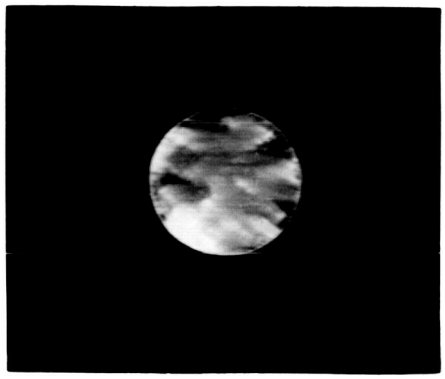

FIGURE 22

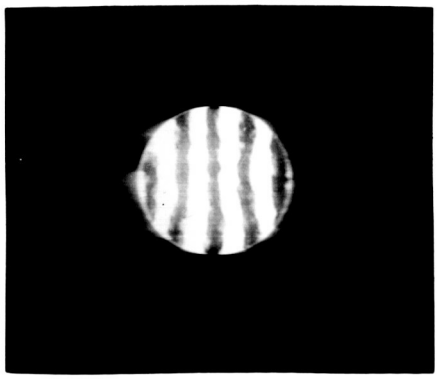

FIGURE 23